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(54) Linear power control for ultrasonic probe with tuned reactance.

(57) There is disclosed herein a driver system for an ultrasonic probe for allowing a user to have proportional control of the power dissipated in the probe in accordance with the position of power dissipation controls operable by the user and for automatically tuning upon user request such that the driving frequency is equal to the mechanical resonant frequency of said probe and such that the reactive component of the load impedance represented by said probe is tuned out. The system uses a tunable inductor in series with the piezoelectric crystal excitation transducer in the probe which has a flux modulation coil. The bias current through this flux modulation coil is controlled by the system. It is controlled such that the inductance of the tunable inductor cancels out the capacitive reactance of the load impedance presented by the probe when the probe is being driven by a driving signal which matches the mechanical resonance frequency of the probe. The resulting overall load impedance is substantially purely resistive. The system measures the phase angle and monitors the load current. This information is used to determine the mechanical resonance frequency by sweeping through a band of driving frequencies and finding the peak load current where the slope of the load current versus frequency function is greater than a predetermined constant. After the automatic tuning to the resonant frequency, the system automatically adjusts the bias current flowing through the flux modulation coil to maintain the substantially purely resistive load impedance for changing power levels. There is also disclosed herein an analog circuit to measure the Phase angle for the load driving signal and to adjust the frequency of the driving signal for best performance. This system includes an integrator to eliminate the effect of offset errors caused by operational amplifiers.

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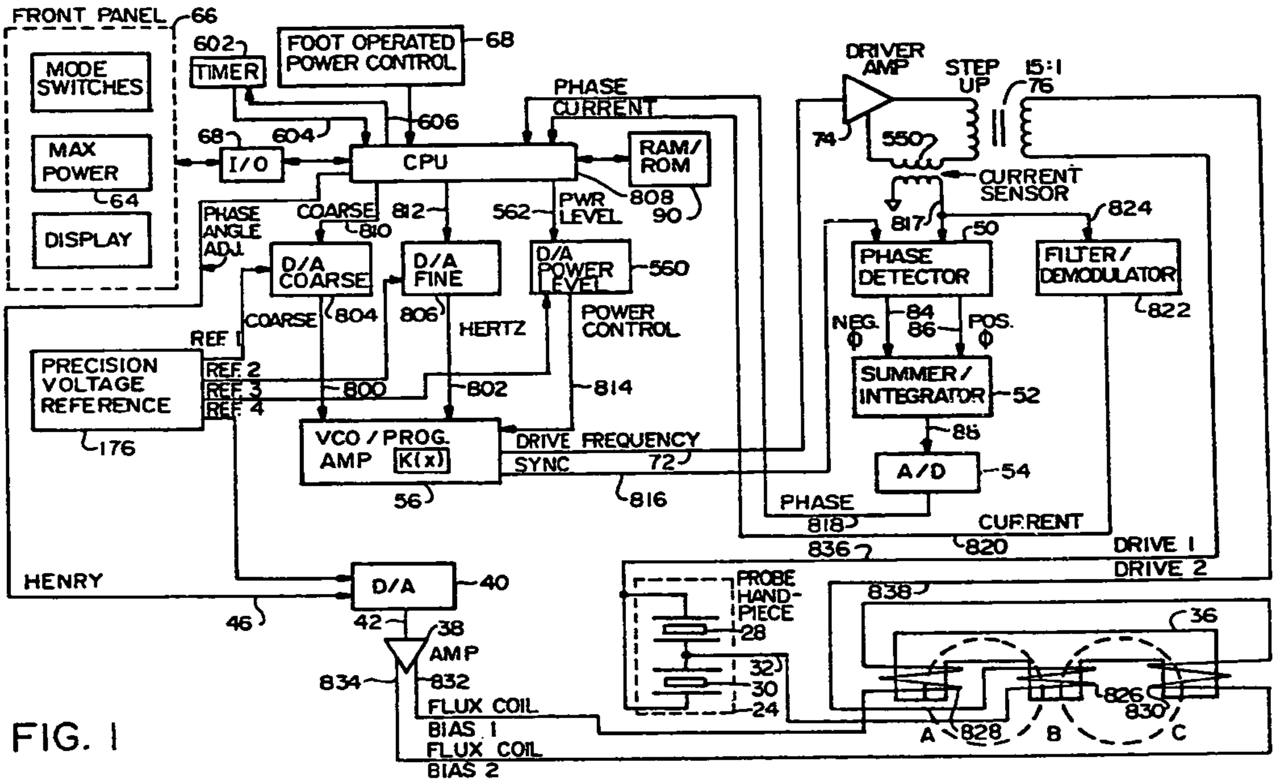
FRONT PANEL 66
MODE SWITCHES
MAX POWER
64
DISPLAY
602
TIMER
FOOT OPERATED POWER CONTROL
68
68
I/O
604
606
CPU
PHASE CURRENT
RAM/ROM
808
90
PHASE ANGLE ADJ.
COARSE
810
812
562
PWR LEVEL
D/A COARSE
D/A FINE
D/A POWER LEVEL
560
COARSE
804
806
HERTZ
POWER CONTROL
REF 1
PRECISION VOLTAGE REFERENCE
REF 2
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REF 4
800
802
814
176
VCO / PROG. AMP K(x)
DRIVE FREQUENCY
SYNC
72
56
816
DRIVER AMP
STEP UP
15:1
76
74
550
CURRENT SENSOR
824
817
50
PHASE DETECTOR
FILTER/ DEMODULATOR
822
NEG. Φ
84
86
POS. Φ
SUMMER/ INTEGRATOR
52
88
A/D
54
PHASE
818
CURRENT
820
836
DRIVE 1
DRIVE 2
HENRY
D/A
40
46
42
38
AMP
834
832
FLUX COIL BIAS 1
FLUX COIL BIAS 2
PROBE HAND-PIECE
28
32
30
24
838
36
826
830
A
828
B
C

FIG. 1

LINEAR POWER CONTROL FOR ULTRASONIC PROBE WITH TUNED REACTANCE

Background of the Invention

The invention relates to the field of phacoemulsification probe driving apparatus, and, more particularly, to the field of tuned reactance process for phacoemulsification.

It has long been known that, in delivery of electric power to inductive loads or capacitive loads, maximum efficiency and maximum delivery of said power occurs when the phase angle between the voltage across the load and the current through the load is zero. The phase angle of a system is related to the power factor. Those skilled in the art appreciate that impedance of any network which includes inductive or capacitive elements in addition to resistive elements is the vector sum of the real component, i.e., the resistive elements, and the imaginary component caused by the presence of the inductive and capacitive elements. If the reactive component is zero, then the impedance of a system is purely resistive, and the resultant vector is coincident with the real axis. In such a circumstance, the phase angle is zero. Power factor is a measure of the relative magnitudes of the reactive and real components in a load impedance. It is related to the relative magnitude of these two vector components.

Power factor is also a measure of the efficiency, of a system in delivering power to a load. Since only resistive components can actually dissipate power, the presence of an inductive or capacitive reactance component in a load impedance will decrease the efficiency of power delivery of the system, since it causes increased power dissipation in the source resistance of the power supply. The reason for this is well understood by those skilled in the art and will not be detailed here. As a consequence of the foregoing reality, it has long been known by utility companies and other practitioners of the power delivery art that to maximize the efficiency of power delivery to a load, it is useful to tune out the reactive component of the load impedance by placing it in series or parallel with an equal and opposite sign reactive component in a tuning circuit so that the resultant load impedance is purely resistive. In such a circumstance the source impedance is said to be the matched conjugate of the load impedance, and the power delivered to the load is maximized.

Power delivered to a load is given by the following expression:

(1) Power = VI cos theta

where V is the voltage drop across the load impedance, and I is the series current flowing through the load impedance, and cos theta is the power factor of the circuit. The power factor is said to be "leading" if the current leads the voltage, and "lagging" if the current lags the voltage.

Ultrasonic probes have traditionally been used for phacoemulsification for rupturing of cataracts in the eye coupled with aspiration of the pieces of tissue disrupted by the probe. There have been developed two classes of probes, one of which is excited by piezoelectric crystals. Such piezoelectric probes traditionally have been rods of metal, such as titanium, having piezoelectric crystals affixed therein to act as excitation sources to cause the rods to vibrate. The piezoelectric crystals are driven with electrical alternating current driving signals having high frequencies, such as 40,000 Hz. The length of the probe is such that it is a multiple of one-half the wavelength of the driving signal. Vibration of the piezoelectric crystal under the influence of the driving signal causes the rod to vibrate at its mechanical resonant frequency.

The piezoelectric crystals which are used as excitation sources in such probes, when coupled with the mass of the probe rod, can be modeled as an equivalent electrical circuit having inductive, capacitive, and resistive components. There is a capacitive component representing the elasticity of the metal of the rod and inductive component representing the mass of the probe. There is also a resistive component representing resistance to motion of the tip of the rod as it hits loads such as tissue or fluids in the eye which tend to dampen the vibration of the tip of the probe. The piezoelectric crystal itself contributes a resistive component which is related to the amount of leakage of current between the terminals of the crystal. The crystal also has a capacitive component which represents the intrinsic electrical characteristics of piezoelectric crystals, i.e., the thickness and the dielectric constant and the area.

As the temperature changes, and as load on the probe changes, the various resistive and reactive components in the equivalent circuit of the probe change values. These changes in the component values change the mechanical resonant frequency of the probe. Unless the driving frequency is changed to correspond with the changed resonant frequencies, maximum power-transfer efficiency will not be achieved.

Further, those skilled in the art understand that maximum power transfer between a source and a load occurs when the impedances of the source and the load are matched so that the load appears to be purely resistive. Therefore, in the case of an ultrasonic probe if the probe load impedance at the resonance frequency has a capacitive reactive

component, the source impedance should have an inductive reactive component of equal magnitude to maximize power transfer between the source and the load. Because of the changing magnitudes of the resistive and reactive components of the combined mechanical and electrical system of a phacoemulsification probe, as the power level changes and as the temperature and load conditions of the probe change, it is difficult, if not impossible with a fixed inductor, to match the source impedance to the load impedance to cancel out the probe's reactive component over a broad range of power levels and frequency variations. An advantage of such a matched, tuned system is that low voltage components may be used since the impedance seen by the source voltage generator is minimized (looking into a two-port network including the tuning inductor).

Accordingly, there has arisen a need for a phacoemulsification probe driver which can be tuned such that the reactive component of the load is canceled as conditions such as power level, temperature, and loading change. Further, there has arisen a need for a probe driver circuit which can alter the driving frequency to match the changed mechanical resonant frequency as power level, temperature, and loading conditions change or as new probes are attached to the system. Further, a need has arisen for a phacoemulsification probe driver with proportional power control such that the user may set a desired power level and that level of power will be transmitted to the probe.

Summary of the Invention

According to the teachings of the invention, there is disclosed herein a method and apparatus for providing substantially proportional power control for a phacoemulsification probe with automatic tuning to the mechanical resonance frequency of the probe and automatic tuning out of the reactive component of the load impedance. The constant tuning to cancel the load impedance reactive component allows the system to maximize the efficiency of power transfer from the driver to the probe. The apparatus and method for tuning the phacoemulsification probe driver frequency to substantially match the changing mechanical resonant frequency of the probe upon request from the user or as power level, temperature, and loading conditions change in some embodiment finds the resonant frequency by sweeping the drive frequency and finding the peak load current where the slope of the load current versus driving frequency function is greater than a predetermined constant. This constant eliminates spurious peaks from being falsely assumed to be resonant peaks.

In the preferred embodiment, the linear power control apparatus includes a microprocessor which is coupled through a serial interface to a foot pedal control manipulated by the user to set the desired level of power. The microprocessor is also coupled to a maximum power level control on the front panel, which is also manipulated by the user to establish the 100% power level. The microprocessor reads the foot pedal position and the position of the maximum power level control on the front panel and scales the signal from the foot pedal to determine the desired power level as a percentage of the maximum level set by the user at the front panel. The microprocessor then generates a digital gain number and sends it to a programmable gain linear power amplifier inside a voltage controlled oscillator. The programmable linear power amplifier amplifies the driving signal by the gain level established by the digital input from the microprocessor. The output of the linear programmable amplifier is then amplified by another power amplifier operating in class AB. The output of this amplifier is applied to a voltage step-up transformer which has its secondary coupled through a tuning inductor to the piezoelectric crystal or crystals which excite the phacoemulsification probe. The microprocessor also controls the frequency of the voltage controlled oscillator in a manner to be described below.

The tuning inductor is the means by which the source impedance of the probe driver circuitry may be adjusted so that the driver circuitry source impedance is maintained so as to cancel the reactive component of the load impedance presented by the crystal and the mechanical system of the probe. The tuning inductor, in the preferred embodiment, is comprised of a ferromagnetic core with three arms extending therefrom. Two of these arms have the DC bias coils wrapped around them. The AC driving signal is driven through a tuning inductor coil wrapped around the third leg and sets up a magnetic flux through the core, part of which passes through the arms around which the bias coils are wrapped. The magnetic flux modulating coil has a DC current flowing therein at an amplitude controlled by the microprocessor. The purpose of the tuning inductor is to allow the microprocessor to control the amount of inductance which is in series with the load impedance such that the source impedance may be tuned to cancel the reactive component of the load impedance for all load, temperature, and power level conditions. Any tunable inductor which can be used to cancel the capacitive reactance of the load will suffice for purposes of practicing the invention.

In order to control the reactive component of the source impedance, the microprocessor needs

to sense the power factor or phase angle between the phasor representing the current waveform for current flowing through the piezoelectric crystal load and the waveform representing the driving voltage across the piezoelectric crystal load. A phase detector is used for this purpose. It has one input which samples the voltage waveform for the driving voltage across the crystal and it has another input which samples the current waveform for the driving current through the crystal. This current waveform sampling is taken from a current sensor in series with the primary side of the voltage step-up transformer. The feedback voltage from this current sensor is proportional to and in phase with current flowing through the primary of the step up transformer. It is the phase angle between the current flowing in the primary and the voltage across the primary as indicated by a SYNC signal from the voltage-controlled oscillator which is in phase with the driving voltage which is tuned by the system to be zero or some other user defined acceptable phase angle so as to cancel the reactance component of the load. Any other means of sensing the phase of the load current will also suffice for purposes of practicing the invention.

The phase detector generates two pulse-width modulated digital signals which represent the magnitude of the phase and its sign. These pulse-width modulated signals are summed and integrated to generate an analog signal representing the magnitude of the phase angle error. This analog signal is converted by an A/D converter to a digital number representing the phase angle error. Any phase angle other than zero represents an out-of-tune condition where the reactance of the probe impedance is not canceled. When the phase angle is nonzero (or whatever acceptable phase angle the user sets in some embodiments), the microprocessor senses this fact and alters the DC current flowing through the magnetic flux modulating coil in the tuning inductor. This alters the amount of magnetic flux in the core passing through the AC driving coils of the tuning inductor, thereby altering the inductance thereof. This process is continued with small changes to the drive current of the D.C. coil until the reactive component of the probe impedance is canceled and the source drive impedance is a matched conjugate of the probe impedance.

In the preferred embodiment, a sweeper software routine sweeps the driving frequency through a range of frequencies known to include all possible mechanical resonant frequencies of commercially usable phacoemulsification probes. During this sweep, the probe drive current is monitored and compared to the highest probe driver current to that point in time. If the current frequency of the driving signal results in a probe drive current which is greater than the current highest probe driver current, the current probe driver current is replaced with the new highest probe driver current value. Slope calculations to determine the slope of the function of load current versus driving frequency are continuously performed. This process is continued until the entire range of frequencies has been surveyed. The frequency corresponding to the highest probe driver current having a slope which is greater than a predetermined constant is then set into the VCO by sending a signal to the frequency modulation input of the VCO causing it to generate a probe driving signal having the corresponding frequency. After the proper driving frequency is determined, a software routine to tune away the phase angle as much as possible is performed. This routine determines the phase angle difference between a constant reference phase angle representing the desired or unavoidable phase angle difference and the actual phase angle. The difference is then used to adjust the D.C. coil bias drive. This process of successive approximation is then continued until the phase angle difference falls within an acceptable range.

The methods of linear power control, impedance matching over wide ranges of conditions, and source frequency tuning to match the resonant frequency according to the teachings of the invention may be understood from the above description of the functions of the apparatus that implements these processes.

The teachings of the invention can be better understood by reference to the following drawings.

Brief Description of the Drawings

Figure 1 is a block diagram of the preferred embodiment of an apparatus according to the teachings of the invention.

Figure 2 is an equivalent circuit for the piezoelectric crystal and mechanical system of the probe.

Figures 3A and 3B are two expressions of the mathematical relationships needed to explain the functioning of the system.

Figure 4 is the simplified equivalent circuit of the probe at the mechanical resonant frequency.

Figure 5 is a symbolic diagram illustrating the interplay between the hardware and software elements of the system.

Figure 6 is a plot of a typical load current versus frequency function illustrating the precharge and postcharge regions symbolically.

Figure 7 is a flow chart of the "minimizer" routine to tune out the reactance component of the load impedance.

Figure 8 is a flow chart of the "def-phase" routine to set a default value for HENRY.

Figure 9 is a flow chart of the "correct" routine to alter the value of HENRY.

Figure 10 is a flow chart of the "capture" subroutine to set HENRY at certain capture limits.

Figure 11 is a flow chart of the "sweeper" subroutine to tune the VCO to the mechanical resonance frequency of the probe.

Figures 12A and 12B are a flow chart of the "cold-sweep" routine which calls the "analysis" routine to do the VCO tuning and manages user interface functions.

Figure 13 is a flow chart of the "analysis" routine.

Figure 14 is a flow chart of the "precharge" routine.

Figure 15 is a flow chart of the "postcharge" routine.

Figure 16 is a flow chart of the "chk-limit" routine to move the tuning window.

Figures 17A and 17B are a flow chart of the "peak" routine that finds the resonance peak by monitoring load current.

Figures 18A and 18B are a flow chart of the "recorder" routine which records load current data and calculates slope.

Figure 19 is a flow chart of the "detector" routine which checks the slope of the load current function against a minimum slope.

Detailed Description of the Preferred Embodiment

Referring to Figure 1, there is shown a block diagram of one embodiment of the apparatus according to the teachings of the invention. A microprocessor 808 is at the heart of the system. The microprocessor 808 controls all the functions which the system performs. According to the teachings of the invention, three separate and independent function are performed, all of which can be performed independently of the other functions. Best performance, however, results from use of all three aspects of the invention in combination.

The purpose, function and interaction of the various components of the system will be explained in the course of explaining each function that the system performs so that the cooperation of each individual element with the other elements in order to accomplish the function will be clear.

It is useful in phacoemulsification probe driver systems to have a substantially linear control over the amount of power dissipated in the probe. In Figure 1, the probe 24 is a metal rod having a conical mechanical amplifier section (not shown) and a projecting nosepiece (also not shown) in the form of a small diameter tube on the mechanical amplifier. Embedded in or otherwise mechanically attached to the metal of the probe 24 are a pair of piezoelectric crystals, 28 and 30. The purpose of these crystals is to excite the metal of the probe 24 to vibrate at its mechanical resonance frequency as the crystals vibrate in response to electrical driving signals on the lines 836 and 838. Together, the piezoelectric crystals 28 and 30 and the mechanical system of the probe 24 can be modeled by the equivalent circuit shown in Figure 2.

Referring to Figure 2, there is shown the equivalent circuit for the electrical and mechanical system of the probe 24. The two resistive components R_p and R_s represent, respectively, the leakage between lines 836 and 838 of the crystals 28 and 30 and the resistance of the mechanical load, e.g., cataract or water or other tissue, touching the tip of the probe. The value of R_s changes drastically when the probe comes into contact with liquid such as water or other fluids in the eye versus free vibration of the probe in air. Computer simulations of the crystal-mechanical system show that R_s can increase drastically with changing conditions.

As power is dissipated in the crystals, the temperature of the probe 24 can increase if sufficient amounts of power are dissipated. The probe 24 has a fluid passageway (not shown) through the tip to which a vacuum is applied such that tissue and eye fluids which the probe contacts may be aspirated into a collection cassette. This causes some cooling of the probe. The temperature rise of the probe thus depends upon the thermal equilibrium between heat flowing into the probe by virtue of power dissipation in the crystals versus heat being taken out of the probe by virtue of cool fluids being aspirated through the probe.

The series network of capacitance C_s and inductance L_s in the equivalent circuit of Figure 2 representing the mechanical aspects of the probe will have a resonant frequency representing the mechanical resonance frequency. Generally speaking, when the crystals 28 and 30 are driven with a drive signal having an electrical frequency matching the mechanical resonance frequency, the crystals will excite the mechanical system of the probe so as to vibrate at the mechanical resonant frequency. In this state, the series capacitance C_s and inductance L_s representing the mechanical aspects of the system will cancel each other out and disappear from the equivalent circuit representing the overall probe load impedance. This leaves an equivalent circuit which is dominated by the capacitance C_p of the piezoelectric crystals as shown by Figure 4.

Thus, the load impedance of the probe, when driven at the mechanical resonance frequency, has a capacitive reactance component. In order to get maximum efficiency of power transfer, this capacitive component C_p of the load impedance must be canceled out or at least somewhat compensated by an inductive impedance in series with the probe.

This compensation for the capacitive reactance of the probe load impedance is accomplished by use of a tuning inductor 36 having an inductance L_T. The tuning inductance consists of a ferromagnetic core having three legs labeled A, B, and C. Legs A and C have wound thereabout D.C. bias signal coils which are connected in series. The middle leg B has wrapped thereabout an A.C. driving signal coil. The purpose of this A.C. driving signal coil is to provide an inductance in series with the load impedance of the probe to help cancel the capacitive reactance of the load impedance at the mechanical resonant frequency. To that end, the A.C. driving signal coil establishes paths of magnetic flux which pass through the ferromagnetic material of legs A, B and C. When direct current is passed through the D.C. bias coils, the amount of magnetic flux in the ferromagnetic coil is altered. When the amount of flux in the core is altered, the inductance of the A.C. driving signal coil changes. Thus, by controlling the magnitude of current flowing through the D.C. bias coils 828 and 830 wrapped around legs A and C (hereafter sometimes referred to as the flux modulation coils) the inductance L_T of the tuning inductor, i.e., the A.C. driving signal coil 826, may be changed. The D.C. bias windings 828 and 830 must be such as to be able to alter the apparent inductance of the A.C. coil 612 between 0 and 30 millihenries.

The flux modulation coils 828 and 830 are coupled to the output of a voltage-to-current amplifier 38. This amplifier receives a voltage input signal from a D/A converter 40. The purpose of the voltage-to-current amplifier 38 is to convert the voltage on the line 42 from the output of the D/A converter to a corresponding magnitude of D.C. bias current flowing through the flux modulation coils 828 and 830.

The D/A converter 40 receives as its input a phase angle adjust digital word HENRY on the bus 46 from the microprocessor. This phase angle adjust word is generated by the microprocessor 808 in the process of running one of the programs described below.

HENRY is generated from certain items of data read by the microprocessor. One of these data items is the phase angle error word PHASE on a bus 818. This phase angle error data represents the phase angle between the phasor representing the driving voltage waveform applied across the crystal load and the phasor representing the current waveform for load current flowing through the crystal. This phase angle error information is developed in part by a phase detector 50. The output of the phase detector is coupled to a summer and integrator 52, which has its output 88 coupled to an A/D converter 54.

To understand how the phase angle error adjust signal is generated on bus 818, the rest of the driving circuitry will be explained as a preliminary matter. The function of the driving circuitry is to drive the crystals 28 and 30 with an A.C. driving waveform which causes the crystals to vibrate at the mechanical resonance frequency of the probe 24. Obviously, the first step in this process is to generate a driving signal having a frequency which is equal to the mechanical resonance frequency of the probe 24. This is done, in the preferred embodiment, by a voltage controlled oscillator 56. In the preferred embodiment, the voltage controlled oscillator includes a linear programmable amplifier.

The output signal of the voltage controlled oscillator on line 72 in Figure 1 is applied to the input of a linear driver amplifier 74. The purpose of this amplifier is to amplify the signal on the bus 72, and apply it to the primary winding of a voltage step-up transformer.

The driving signal on line 72 is generally a sinusoid having an RMS voltage level related to the desired power dissipation. This signal is amplified in a class AB mode by the driver amplifier 74.

The output of the amplifier 74 is applied to the primary of a voltage step-up transformer 76. A current sensing transformer 550 is coupled in series with the return line from the primary of the transformer to the operational amplifier 74. The secondary of the transformer 76 is coupled to the lines 836 and 838. The line 838 is coupled to one end of the A.C. driving signal coil 826 on the tuning inductor. The other terminal of coil 826 is coupled via a line 32 to one terminal of the crystals 28 and 30 (which are coupled in series). The line 836 is coupled to the return side of the piezoelectric crystals 30 and 28. Thus the current flowing in the secondary of the step-up transformer 76 is the series current flowing through the crystals 28 and 30 of the probe 24 and the A.C. signal driving coil 826.

The CPU 808 needs feedback signals regarding two things to do its tuning functions. First, the CPU 808 must know the phase angle difference between the driving signal voltage and the resulting load current. Also, the CPU must know the amplitude of the current flowing in the load. To determine the phase angle difference, the phase detector 50 and a current sensor transformer 550 are used. The phase detector has one phase input coupled by line 817 to the secondary winding of the current sensor 550 and has another phase input coupled to a signal SYNC on line 816 from the voltage control oscillator. As in the other embodiments described herein, when there is no phase difference, no pulses appear on either of the output lines 84 or 86. However, when positive phase difference exists, a train of pulse width modulated pulses appear on line 86 with the width of

the pulses indicative of the amount of the phase angle difference. Likewise, when a negative phase angle difference exists, a train of pulse width modulated pulses appears on line 84 with the width of the pulses indicative of the magnitude of the phase angle difference. The summer/integrator 52 and analog-to-digital converter 54 operate as previously described to generate the digital signal PHASE on line 818, which is indicative of the magnitude of the phase angle error. The signal is coupled to the CPU 808. The phase detector 50 uses the SYNC signal output on line 816 from the voltage-controlled oscillator because this signal is cleaner and leads to better phase detection than where the phase detector 50 has its other input coupled to the DRIVE FREQUENCY signal on line 72.

Since the voltage waveform on line 72 is in phase with the voltage waveform across the primary of the step-up transformer, the phase detector 50 can sample the voltage on the line 72 with the assurance that the waveform on the line 72 is in phase with the voltage across the step-up transformer 76. To determine the relative efficiency of power transfer from the driver to the probe, the phase angle between the voltage across the step-up transformer primary and the current through the primary must be determined. The phase detector does this by comparing the phase of the voltage waveform on the line 72 to the phase of the current flowing in the primary of the step-up transformer 76, as determined by a current sense transformer 550. This current sense transformer has its primary in series with the primary winding of the voltage step up transformer 76. The current sense transformer 550 is, itself, a voltage step-up transformer such that the voltage generated across the primary winding by the current flow through the primary of the voltage step-up transformer 76 generates a voltage in the secondary of the current sense transformer 550 which is a multiple of the voltage across the primary. The multiple depends upon the turns ratio as between the primary and the secondary windings of the transformer 550. The current sense transformer 550 has less parasitic induct ance and parasitic capacitance than a current sense resistor which eliminates one possible source of error in determining when the frequency of the driving signal is most closely matched to the mechanical resonant frequency of the probe. However, in alternative embodiments, such a current sense resistor may be used. Since the software uses the voltage swings on the secondary of the current sense transformer 550 as part of the information needed to determine the phase angle, it is important to derive clear signals with a high signal to noise ratio. The current sense transformer 550 improves the signal-to-noise ratio by stepping up the voltage across the primary winding of the transformer 550 to a level well above any noise.

In the preferred embodiment, the output signal from the secondary winding of the current sense transformer 550 is applied directly to one input of the phase detector 50 which includes suitable interface circuitry to convert this signal to information needed to determine the current flow. In alternative embodiments, the R.M.S. value of the A.C. signal from the secondary winding may be converted to a D.C. signal value by an operational amplifier. The magnitude of this signal indicates the amplitude of the current flowing in the primary of the step up transformer 76, and, therefore, is indicative of the level of drive current in the probe 24. This D.C. signal may be coupled to one input of a two channel analog-to-digital converter. The analog-to-digital converter converts the D.C. level on to a digital signal which indicates the level of the drive current flowing in the primary winding of the step-up transformer 76. This information is used by the "Sweeper" software routine to be described below in determining the frequency for the drive signal on line 72 which matches the mechanical resonance frequency of the probe 24.

The phase angle between the voltage waveform on the line 72 and the current waveform in the primary of the transformer 76 is indicative of the degree of canceling of the reactive component of the probe impedance by tuning of the tuning inductor 36. A small or zero phase angle indicates substantially complete canceling of the reactive component. The phase detector 50 is used to determine this phase angle by comparing the signals on lines 816 and 817. Each time the signal on the line 72 makes a zero crossing, the SYNC signal so indicates. Each time the signal on line 817 crosses zero, the phase detector 50 senses this event. These changes of states on lines 817 and 816 are analyzed by the phase detector 50 to determine the then existing phase angle. Since the signal on line 72 is the driving voltage and the signal on line 817 is proportional to the current passing through the probe 24 in response to the signal on the line 72, the difference in times of occurrence of the changes of states on the lines 817 and 816 can be decoded into the corresponding phase angle.

The phase detector 50 is a conventional Motorola integrated circuit or any equivalent which is commercially available.

The magnitude of the phase angle error is indicated by the width of the pulses on lines 84 and 86. The purpose of the integrator 52 is to average out the pulses over time so that the system has a smooth D.C. response to changes in the phase angle. The A/D converter 54 converts the analog phase angle error signal to a digital phase angle error word on bus 48.

The microprocessor 808 performs the linear

power control, impedance-matching, and frequency-tuning functions of the invention by running a program stored in local RAM 90. This memory also includes ROM for storage of lookup tables and other information which does not change over the life of the system.

Referring to Figure 3, equation (A), there is shown the expression which defines the relationships which exist when the piezoelectric crystals are being driven at the resonant frequency of the mechanical system. Equation B in Figure 3 defines the value of the tuning inductance when it is in the tuned condition when the crystals are being driven at the resonant frequency of the mechanical system. Equation A represents the expression for the resonant frequency of the mechanical probe system for any particular temperature.

In Figure 2, the mechanical system is represented by the components in the equivalent circuit, labeled R_S, C_S, and L_S. The value of the component R_S represents the mechanical load engaged by the tip of the probe. The component C_S represents the elasticity of the metal in the probe. The component L_S represents the mass of the probe. The value of the components C_S change with changing temperature. The temperature may change either because the ambient temperature changes or because of power dissipated in the probe through excitation of the crystals. The value of the component R_S changes greatly with the loading of the probe.

The other components of the crystal/probe system equivalent circuit are C_P and R_P. The component C_P represents the parallel electrical capacitance of the crystals 28 and 30 in Figure 1. The component R_P represents the leakage of electrical current between the terminals of the crystals.

At the mechanical resonance frequency, the reactive component represented by C_S (jw C_S) is exactly equal to and opposite in sign to the reactive component L_S (1/jw L_S). Since these two reactive components cancel each other out, the equivalent circuit for the crystal/probe system is as shown in Figure 4. As can be seen from Figure 4, the equivalent circuit has a substantial capacitive reactance of the crystals 28 and 30. Thus the load impedance has a real component represented by the value of the resistors R_S and R_P in parallel, and a re active component of a capacitive nature represented by the capacitance C_P. According to the teachings of the invention, maximum power efficiency will be achieved by tuning the tuning inductor L_T so as to cancel out the reactive component and the load impedance represented by C_P. When the crystals 28 and 30 are driven at the resonant frequency of the mechanical system for any particular temperature, the necessary value for the tuning inductance is given by equation B in Figure 3.

As can be seen from equation B, the value for the tuning inductance is highly dependent on the value for the resistive components R_S and R_P and upon the value of the parallel electrical capacitance of the crystals 28 and 30. This means that the necessary value for the tuning inductance to keep the probe system in proper tune will change with changing temperature, changing loading conditions, and changes in the level of power dissipated in the probe by the driving system. The reason for this is that either changes in ambient temperature or power dissipation in the probe raises the temperature of the probe and therefore affects the elasticity of the material. This changes the value of the component C_S in the equivalent circuit of Figure 2 and therefore changes the mechanical resonant frequency as defined by equation A of Figure 3. Changing loading conditions also change the mechanical resonant frequency because, in addition to changing the value of R_S in Figure 2, changing load also affects the value of L_S because the load becomes an effective part of the mass of the system. This also changes the value of the mechanical resonant frequency defined by equation A by Figure 3.

There is also provided a watchdog timer circuit 602 which serves as a safeguard against software or computer failure. The watchdog timer is constantly counting up toward a timeout number and will be continually reset by the CPU 808 by a signal on the line 606 before the timeout number is reached as long as the CPU 808 is functioning properly. If the CPU gets trapped in an endless loop or somehow fails to reset the watchdog timer 602, the timer will time out and assert a nonmaskable interrupt on line 604. The CPU 808 is slaved to the nonmaskable interrupt and will always be vectored to the service routine which serves the nonmaskable interrupt regardless of whether the CPU is in an endless loop or not. This service routine shuts down the system as a safety precaution.

The voltage-controlled oscillator/programmable gain amplifier 56 has two frequency control inputs: a coarse input 800 and a fine input 802. These two inputs receive the signals COARSE and HERTZ, respectively, from digital-to-analog converters 804 and 806, respectively. These digital-to-analog converters receive digital signals from the CPU 808 on lines 810 and 812, respectively. These digital signals define the analog levels for the signals on lines 800 and 802 and thereby control the frequency of the output drive signal DRIVE FREQUENCY from the voltage-controlled oscillator on line 72.

Each of the digital-to-analog converters 804 and 806 receives a reference voltage from a preci-

sion voltage reference source 176 in the form of the signals REF 1 and REF 2, which are used as reference voltages for purposes of scaling the analog voltages on lines 800 and 802.

To generate the signals on lines 810 and 812 and do the many other functions described here, the CPU 808 runs the software described in the flow charts of the various figures described below. The CPU 808 is a Z-80 card which is commonly available. The voltage-controlled oscillator programmable amplifier 56 is manufacture by Exar Corporation, Model XR2206.

The power level for the DRIVE FREQUENCY signal on line 72 is controlled by the foot-operated control 68 and the CPU 808 in combination with linear power control software 844 in Figure 5. The CPU 808 outputs a power control signal PWR LEVEL on line 562 to a digital-to-analog converter 560. This digital-to-analog converter also received a reference voltage input signal REF 3 from voltage reference source 176. The digital-to-analog converter 560 generates an analog control signal called POWER CONTROL on line 814 which is coupled to a gain control input for the programmable gain amplifier portion of the voltage-controlled oscillator. The signal POWER CONTROL on line 814 controls the amplitude of the output signal DRIVE FREQUENCY on line 72, thereby controlling the power delivered to the handpiece 24.

In the preferred embodiment, the user establishes the desired gain level by manipulation of two controls. The first control is the maximum power control 64 on the front panel 66. With the max power control 64, the user establishes the maximum power level desired. The microprocessor 808 reads this maximum power level through an I/O circuit 68 of conventional design. In one embodiment, the I/O circuit 68 is an SB8466 board manufactured by Micro/Sys of Glendale, California. Any conventional method and apparatus for performing the I/O transactions between the microprocessor and the front panel 66 will suffice for purposes of practicing the invention.

The other user-operable control with which the desired power level is set is a foot pedal 68. This control allows the user to establish the desired power level as a percentage of the maximum power set by the control 64 by depressing a pedal with his/her foot. The depression of the foot pedal operates a transducer which may be read by the microprocessor 808 through interface circuitry (not shown) of conventional design. In the preferred embodiment, the foot pedal 68 is attached to a surgical instrument called the MVS-XIV or MVS-XX (both trademarks of Alcon Laboratories, Inc.) manufactured by the Alcon Surgical Instrumentation Facility of San Leandro, California which is described in U.S. patent 4,470,654 which is hereby incorporated buy reference. This "middleman" architecture is not critical to the invention, and a direct connection between the microprocessor 808 and a foot pedal 68 with conventional interface circuitry may also be used. With the MVS-XIV present, however, the aspiration vacuum is generated to support the operation being performed with the probe which is quite convenient. This vacuum is coupled by a vacuum line (not shown) to the probe 24.

The microprocessor 808 performs a scaling operation using data from the foot pedal 68 and from the maximum power control 64. The microprocessor 808 simply combines the two numbers from the max power control 64 and the foot pedal 68 to determine the percentage of full-scale power currently desired by the user. This number is then output on the bus 562 to the D/A converter 560.

The load current feedback signal CURRENT on line 820 is generated by a filter demodulator circuit 822 coupled to the current sensor 550 coupled in series with the primary winding of the output transformer 76. The input signal on line 824 to this filter demodulator is essentially a sine wave having the frequency of the driving signal on line 72 and having an amplitude which is related to the amplitude of the drive signal on line 72. The CPU 808, however, is only interested in the level of the envelope of the "peak"s of the alternating current signal on line 824. Therefore, the filter/demodulator circuitry 822 can be any conventional demodulation circuitry for AM demodulation. Specifically, it comprises a rectifier to convert the A.C. signal to a train of D.C. pulses and a filter to smooth these D.C. pulses out so as to create a D.C. signal having an amplitude which is related to the amplitude of the envelope of the signal CURRENT on line 820. This signal tells the CPU 808 how much load current the probe, i.e., handpiece, 24 is drawing through the output transformer 76. Since at resonance, the load current will be a maximum, the CURRENT signal is used to detect when the resonance occurs by detecting the "peak" load current and examining the slope of the load current versus frequency function. When the actual resonance frequency is found, the frequency of the drive signal on 72 at which this resonance occurred is noted by the CPU 808 and, thereafter, the CPU controls the voltage-controlled oscillator 56 so as to deliver this frequency at all power levels commanded by the foot-operated power control 68 until such time as retuning is performed automatically or is requested by the user. Both of these options are contemplated as within the teachings of the invention.

The process of tuning the voltage-controlled oscillator to find the resonance frequency is an ongoing foreground process which occurs whenever a routine called "sweeper" is performed. In

some embodiments, the "sweeper" routine is performed periodically and in some embodiments, the "sweeper" routine is performed only when called by the main loop under conditions such as power being first applied to the handpiece, a new handpiece is attached etc. Thus, as conditions such as probe temperature and load change so as to alter the resonance frequency of the probe, the new resonance frequency is found in some embodiments, and the voltage-controlled oscillator is commanded through the digital signals on line 810 and 812 to deliver the drive signal on line 72 at the new resonance frequency.

The CPU 808 from time to time also checks the phase angle difference between the drive signal voltage and the load current through monitoring of the signal PHASE on line 818. In the preferred embodiment, this process is stopped and the tuning inductor is tuned to minimum inductance during a resonance tuning interval when the "sweeper" routine is active in tuning the voltage-controlled-oscillator. A "minimizer" software routine performs the phase angle tuning after the "sweeper" routine finishes its process of locating the mechanical resonance frequency and tuning the VCO to output a drive signal at this frequency. When the "minimizer" routine is active, and the phase angle difference becomes larger than a desired value, the CPU 808 acts through a digital-to-analog converter 40 and an amplifier 38 to alter the inductance of a tunable inductor 36 so as to cancel the capacitive reactance of the load. This minimizes the phase angle difference between the driving signal voltage and the load current. The inductance of the tuning inductor is altered by changing the flux in the tuning inductor core through use of D.C. bias coils 828 and 830. These bias coils are connected in series and are driven by the signals FLUX COIL BIAS 1 and FLUX COIL BIAS 2 on the lines 832 and 834. The D.C. bias existing between the lines 832 and 834 is controlled by a digital signal HENRY on line 46 from the CPU 808. This digital signal is input through the digital-to-analog converter 40, which also receives a D.C. voltage reference level signal REF 4. The digital-to-analog converter converts the digital level represented by the signal HENRY to an analog signal on line 42 which controls the output of an amplifier 38 so as to drive the signal lines 832 and 834 with the appropriate D.C. bias level.

Finally, note that the drive signal to the probe handpiece on lines 836 and 838, i.e., the signals DRIVE 1 and DRIVE 2, respectively, are coupled through the tunable inductance coil 826 such that the DRIVE 2 signal is coupled to the common node between the crystals 28 and 30 while the DRIVE 1 signal is coupled collectively to the outer nodes of the crystals 28 and 30. In other words, center drive between the two crystals 28 and 30 is used.

Referring to Figure 5, there is shown another representation of the combination of hardware and software which cooperates to implement the teachings of the invention. Again, like numbers between Figures 5 and 1 indicate that the circuitry is similar and performs a similar function. The handpiece is represented by the load 24. The variable frequency variable amplitude driving signal for the load appears on the line 836/838 and is generated by the driver 74/76. The circuitry inside the dashed line 56 represents the voltage-controlled oscillator 842 and the linear programmable amplifier 840. The gain control signal to the linear programmable amplifier 840 is the PWR LEVEL signal on line 814. The voltage-controlled oscillator 842 has a fine frequency control signal HERTZ on line 802 and a coarse frequency control signal COARSE on line 800. Power dissipation is controlled by a linear power delivery software routine 844 combined with the CPU 808 an a foot-operated control 68. This power delivery routine 844 generates the signal PWR LEVEL on line 814. The power delivery routine 844 has two interlocks represented by the TUNE flag represented by line 846 and the STOP POWER flag represented by the line 848. The TUNE flag will be set when a tuning routine called "sweeper", represented by box 850, indicates that the load 24 has not been properly tuned and that power should not be applied. The STOP POWER flag represented by line 848 will be set when a ground fault detect routine represented by box 852 indicates that a ground fault has been detected. A ground fault occurs any time certain conditions of three bits stored in a latch 823 occur. These three bits are set, respectively, by the presence of the SYNC output signal on line 816, presence of an output on line 824 from the current sensor and the presence of a connected handpiece as indicated by a signal HANDPIECE CONNECTED on line 825. A typical ground fault condition would be that no handpiece is connected. Another would be that there is a SYNC output signal but there is no output signal on line 824 indicating that no load current is flowing.

The current through the load 24 is sensed by the current sensor 550. The current sensor is coupled to a shaper circuit 854 to condition the signal on line 824 for use by the phase detector 50. The phase detector also receives the SYNC signal on line 816 through a shaper 856 which serves to condition the SYNC signal for use by the phase detector 50. The phase detector is a Motorola MC4044 integrated circuit in the preferred embodiment.

The phase detector output is coupled by a compensation network 52/54 to the CPU (not separately shown). The output of the compensation network is the signal PHASE on line 818.

The output of the current sensor 550 on line 824 is also coupled to a rectifier 858 and a filter 860 which combine to amplitude demodulate the signal on line 824 and generate a D.C. varying signal called CURRENT on line 820 which is proportional to the magnitude of the envelope of the signal on line 824. The signal CURRENT on line 820 is read by the CPU 808 and used in the "sweeper" software routine to tune the voltage-controlled oscillator 852 to output a drive signal on line 860 which has a frequency which matches the mechanical resonant frequency of the load 24. The "sweeper" routine and all the other software routines will be explained functionally in terms of flow charts and any code that implements the functions described in these flow charts will suffice for purposes of practicing the invention. The "sweeper" routine causes two main output signals to be generated by the CPU 808 to control the frequency of the voltage-controlled oscillator 842. These two digital output signals are the signals COARSE and HERTZ on lines 800 and 802, respectively.

The "sweeper" routine also sets a LOOP flag, represented by line 864, to disable the operation of a "minimizer" routine to tune away any PHASE angle error and represented by box 866. The "minimizer" routine serves to determine the current PHASE angle error between the driving signal voltage and the load current and to alter the inductance of a tuning inductor, represented by box 36, so as to minimize or eliminate this PHASE angle error. It is undesirable to perform this process while the voltage-controlled oscillator is being tuned to the resonant frequency because any inductance by the tuning inductor might lead to finding a false resonant frequency. Thus, the loop flag 864 is used to disable this process during activity by the "sweeper" routine.

The "minimizer" routine 866, when activated, causes the CPU 808 to read the signal PHASE on line 818 and to generate an output signal HENRY on line 46 to the driver 40. The output of the driver 40 is an analog D.C. bias signal on line 832/834. This signal is transformed by a D.C.-to-HENRY transformation circuit implemented by the tuning inductor 36 and represented by the box 36. Line 868 represents the effect of the changing magnetic flux in the tunable inductor 36 thereby altering the inductance of the tuning inductor in series with the load and causing the load impedance to look as close to a pure resistance as possible.

A filter 870, implemented in software as a delay function, is used to control the loop frequency response. This delay is necessary to stabilize the operation of the servo loop used to minimize or eliminate the PHASE angle error. Because this servo loop includes a tunable inductor which cannot change states as rapidly as the computer can compute correction factors, each correction is delayed until the servo loop has had a sufficient opportunity to implement the previous correction. Implementation of each correction is by alteration of the inductance of the tunable inductor. The filter 870 also represents a software routine which sets the level of the output signal HENRY on line 46 at a predetermined statistically determined nominal operating point for most handpieces prior to release of control of the power control function to the surgeon manipulating the foot-operated control 68. This operating point is empirically determined as the nominal operating point for most handpieces which can be connected to the system. The software filter routine 870 sets HENRY at this nominal operating point during a postcharge routine which is part of this filter function and sends a signal to the power delivery routine 844 to cause it to apply full power to the load for three seconds prior to release of control to the surgeon. The interaction between the software filter routine 870 and the power delivery routine 844 is represented by the line labeled postcharge 872 although the postcharge routine is software and not a signal, signal line or a flag. This postcharge routine enables smoother operation of the system since the operating point of the load has already been set at a point which is very close to the correct operating point prior to allowing the surgeon to change the system's operating conditions. As the surgeon changes the system operating conditions such as the level of power applied to the handpiece, the mechanical loading on the handpiece, the probe temperature and so on, the system automatically compensates for changes in phase angle and mechanical resonance frequency in some embodiments, thereby constantly keeping the load 24 tuned to optimum operating conditions.

Referring to Figure 6, there is shown a typical plot of load current versus frequency for a typical "sweeper" tuning cycle. The resonant frequency of the probe is found where the load current is at a "peak", as shown at 876, and where the slope of the load current change versus frequency change is below a specified level. The software of the "sweeper" routine finds the resonant "peak" by finding the "peak" load current and examining the slope of the function of load current versus frequency at least at this "peak". In some embodiments, continuous slope calculations are performed but this is not critical. The slope calculation can be made only at what appears to be each new "peak". If this slope at the "peak" is within predetermined limits in some embodiments or less than a predetermined slope in the preferred embodiment, then the "peak" is accepted as a legitimate resonance "peak". If not, the "peak" is rejected a spurious "peak" not at the mechanical resonance

frequency. The software of the "sweeper" routine also performs specific operations during a "precharge" interval to improve performance of the servo loop for tuning the tunable inductor. During the "precharge" interval, the software of the "sweeper" routine causes the CPU to output a predetermined value for the control signal HENRY. After this predetermined level is established, a delay is imposed to allow the inductance of the tuning inductor to change to the new value established by the value of the control signal HENRY. No changes in the drive frequency to the probe are allowed during this delay of the "precharge" interval. During the "precharge" interval, the value of the control signal HENRY is changed to a very large voltage so as to cause the D.C. bias coils 828 and 830 in Figure 1 to saturate the core of the transformer 36 with magnetic flux. This minimizes or eliminates any inductive characteristic of the tuning coil 826. This is desirable so that the inductance of the tuning inductor does not play a role in establishing the resonant frequency found by the "sweeper" routine. Since the reactance of an inductor changes with changing frequency, having the tuning inductor in the circuit during a sweep could lead to a false resonance. The "precharge" routine eliminates the possibility.

Referring to Figure 7, there is shown a flow chart for the "minimizer" routine 866 in Figure 5. This routine starts at step 880 with a test to determine whether the foot switch is down, indicating that the surgeon desires to apply power to the probe and that the LOOP flag is in a state indicating that the "sweeper" routine has tuned the system such that the voltage-controlled oscillator is now operating at the resonance frequency of the probe. The purpose for step 880 is to not allow the "minimizer" routine to minimize the phase angle error unless power is being applied to the probe and the system has been tuned to the mechanical resonance frequency of the probe. The "minimizer" routine is called 30 times per second by a timed interrupt. Thus the PHASE minimization function of the "minimizer" routine is performed in background to the operations in the main loop.

If both the foot switch is down and the LOOP flag indicates that tuning of the tuning conductor is permissible, processing advances to step 882. In this step, a variable SUPPRESS is tested to determine if its value is greater than 30. The SUPPRESS variable is a variable which is used to cause a delay of one second from foot pedal depression before any further corrections of the control signal HENRY are allowed. Since the "minimizer" routine is called 30 times per second, and the SUPPRESS variable is incremented by 1 by step 884 upon each call until the SUPPRESS variable has a value greater than 30, a one second delay is thereby implemented. The purpose for this delay is to improve the response of the system when the foot switch is first pressed by the surgeon. Because of the characteristics of the servo loop, when a servo correction is made, power dies momentarily while the servo loop stabilizes at its new operating point. This is because of the characteristics of the tuning inductor and the inability to change current flowing through an inductor instantaneously. Since the surgeon expects immediate response when the foot switch is pressed, the delay is used to not allow any corrections within the first second after depression of the foot switch so that power response appears to be instantaneous.

Returning to step 880, if the result of this test is false, meaning either that the foot switch is not depressed or that the LOOP flag indicates that the "sweeper" routine is still tuning, processing branches to step 886, where the SUPPRESS variable is set to zero. Thereafter, processing flows to step 888, where the value of the PHASE variable is arbitrarily set to the constant 2047. Normally the PHASE variable is set by the value of the PHASE control signal on line 818 received from the compensation network 52 54 in Figure 5. However, the PHASE variable can be set at a constant, if desired. The value of the PHASE variable can vary from zero to 4095. The midpoint of this range is 2047 and corresponds to a zero-degree phase angle error. The phase angle range of 2047 ± 2047 corresponds to a phase angle error of plus or minus 180 degrees. Thus, step 888 is equivalent to arbitrarily setting the phase angle error at zero. Thereafter, processing flows to step 890 to exit the "minimizer" routine and return to the calling process.

Returning to step 882, if the value of the SUPPRESS variable is less than 30, the step 884 increments the variable by 1, and processing flows to steps 888 and 890. If however the value of the SUPPRESS variable is found to be greater than 30, the one-second delay implemented thereby has elapsed, and a correction of the phase angle error can begin. The first step in this process is symbolized by block 892 which calls the "default phase" subroutine.

Referring to Figure 8, there is shown a flow chart of the "default phase" subroutine called by the "minimizer" routine of Figure 7. The first step in the default phase routine is step 896, where the value of the PHASE variable is tested to determine if it is greater than the constant 2047. The PHASE variable will have been set by the value of the input signal PHASE on line 818 in Figure 5. Since the value 2047 for the PHASE variable indicates a zero degree phase angle, step 896 is a test for the existence of a positive phase angle. If the phase

angle is positive, that phase angle is used for the default phase, and processing flows to step 898 to return to the "minimizer" routine at step 900. If the phase angle error is negative, or less than 2047, processing flows to step 902 where the value of the PHASE variable is arbitrarily set to a default constant of 3072. Thereafter, processing flows to step 904, where the software causes the microprocessor to output a value for the control signal HENRY equal to 3072. Thereafter, processing returns to the "minimizer" routine of Figure 7 at step 900.

Step 900 of the "minimizer" routine is a call to a subroutine called correct. Referring to Figure 9, there is shown a flow chart of the subroutine "correct". The first step in the subroutine "correct" is a test of the MARGIN variable to see if it is greater than a variable ALLOWED. The variable MARGIN is equal to the absolute value of another variable called DELTA. DELTA is a variable calculated by a step 908 in Figure 7 and is indicative of the size of the phase angle error. Specifically, step 908 in Figure 7 calculates DELTA by subtracting a constant phase angle error THETA from the value of the PHASE variable set by the actual phase angle error. THETA is a constant phase angle error introduced by the circuitry of the servomechanism which cannot be eliminated. The ALLOWED variable sets a minimum phase angle error which is acceptable. If the MARGIN variable is greater than the ALLOWED variable, then adjustment to the tuning inductor must be made. If the MARGIN variable is less than the ALLOWED variable, then the phase angle error is within acceptable limits and no correction need be made. In this event, processing flows to step 910, which returns processing to the calling process, i.e., processing flows to step 908 in Figure 7.

Returning to step 906, if the phase angle is greater than the allowed minimum phase angle, processing flows to step 912, where the value of a variable called TWEAK is set at the value of DELTA divided by 2. Input/output step 914 is then performed where the software causes the microprocessor to set the value of the control signal HENRY equal to the old value for HENRY plus the value of the variable TWEAK calculated in step 912. Next, a step 916 is performed wherein a subroutine called "capture" is called.

Referring to Figure 10, there is shown a flow chart of the "capture" subroutine. The first step in the subroutine is the test represented by block 918. This test determines whether the value of the control signal HENRY is greater than the value of a variable called LOW-LIMIT. If the value of the control signal HENRY is less than the value of the constant LOW-LIMIT, then step 920 is performed wherein the value for the variable HENRY is set equal to a constant called RETREAT which is basically a constant at or near the opposite rail or limit. This value for HENRY is then output by the microprocessor on line 46 to the driver 40 38 in Figure 5. If the value of the variable HENRY is greater than the constant LOW-LIMIT, then step 922 is performed, where the value of the HENRY variable is tested against a high limit symbolized by the constant HI-LIMIT. If the value of HENRY is less than HI-LIMIT, then step 924 is performed to return processing to the calling process, i.e., step 910 in the subroutine "correct", illustrated in Figure 9. If the value of the variable HENRY is greater than the constant HI-LIMIT, then a step 926 is performed wherein the value of HENRY is set equal to the value of the constant HI-LIMIT.

The purpose of the "capture" routine is to capture the value of the variable HENRY within a range defined by the constants RETREAT and HI-LIMIT. This prevents the control signal HENRY from making excursions outside the desired range and causing the servo loop controlling the tuning inductor to have to make large corrections to minimize the phase angle. Making large corrections slows the response time of the servo loop down because each large correction requires changing the value of the tuning inductor inductance by large amounts. Since this inductor cannot change its inductance rapidly because the level of current flow in the D.C. bias coils instantly, such large changes take long intervals.

The return from the "capture" routine is to the "correct" routine at step 910. The return from step 910 of the "correct" routine is to step 908 of the "minimizer" routine shown in Figure 7. Step 908 calculates the value of the variable DELTA by reading the current value of the PHASE variable as set by the PHASE control signal received from the compensation network 52-54 in Figure 5. The value of PHASE has subtracted from it the value of the constant THETA.

Next, a step 928 is performed in the "minimizer" routine to divide the value of DELTA by a factor of 8. This prevents corrections of the value of the control signal HENRY which are large. Thereafter, step 890 is performed to exit the "minimizer" routine and return processing to the calling point of the main loop of the software. The above-described processing of the "minimizer" routine is performed 30 times per second.

Referring to Figure 11, there is shown a flow chart of the "sweeper" routine, which tunes the frequency of the voltage-controlled oscillator to match the mechanical resonance frequency of the handpiece. The first step in the "sweeper" process is symbolized by block 934, which tests a MISTUNE variable to determine if the second least significant bit is a logic one. This bit is used by other routines (not shown) in the software to man

age an "analysis" subroutine to be described further below. If for any reason the handpiece must be retuned, the second least significant bit of the MISTUNE variable will be set to a logic 1. This can occur when a new handpiece has been connected, or for other reasons such as a user request in some embodiments. For present purposes, the "analysis" subroutine should be understood as the software which causes the microprocessor to alter the frequency of the voltage-controlled oscillator until the mechanical resonance frequency of the handpiece is found or, for some reason, the resonance is not found and a FAILURE flag is set.

If the second least significant bit of the MISTUNE variable is found to be a logic 1, processing flows to step 936, which represents a call to the "cold-sweep" subroutine. The "cold-sweep" subroutine calls the "analysis" subroutine after setting up appropriate input conditions so as to tune the voltage-controlled oscillator. Upon return from the "cold-sweep" subroutine, the return step 938 in the "sweeper" routine is performed to return control to the calling process in the main loop (not shown).

If the second least significant bit of the MISTUNE variable is a logic 0, then processing flows to step 938, which represents a return to the calling process in the main loop. The details of the main loop of the program, including the calling process, are not critical to understanding the invention, and are not described further herein.

Referring to Figure 12A, there is shown a flow chart of the "cold-sweep" subroutine. The purpose of the "cold-sweep" subroutine is to tune the handpiece by invoking the "analysis" subroutine and to handle user interface functions in the form of audible feedback and a light-emitting diode on the front console to give the status of the tuning process. The "cold-sweep" subroutine also invokes the "postcharge" subroutine previously described. As earlier noted, the "sweeper" routine disables the PHASE "minimizer" routine 866 in Figure 5 through use of the LOOP flag 864 in Figure 5 during the tuning process.

To implement the function of visual feedback to the user, step 940 disables a light-emitting diode on the front panel near the connector where the handpiece is attached to the system. The next step, symbolized by block 942, is to cause this light emitting diode to blink. Thus, the user knows that a tuning process is underway when the light emitting diode is blinking.

It is important that only compatible phacoemulsification handpieces be connected to the system. To this end, a step 944 is performed to test the connected handpiece to determine if it is compatible. Any sensing scheme to determine the compatibility of the handpiece will suffice for purposes of practicing the invention, and the details of this sensing are not critical to understanding of the invention. If the test of block 944 determines that an incompatible handpiece has been connected to the system, then step 946 is performed to return processing to the calling routine, i.e., "sweeper", at step 938. Return step 938 then returns processing to the calling process in the main loop. Thus, when an incompatible handpiece is connected to the system, "cold-sweep" does not invoke the "analysis" subroutine, and no tuning can occur.

If test 944 determines that a compatible handpiece is connected, a step 948 is performed wherein a RANGE variable is set to a constant FULL. The RANGE variable is a control variable used to enable or disable performance of the "analysis" subroutine. If RANGE is set to full, the "analysis" subroutine will perform its tuning function. If, on the other hand, the RANGE variable is set to the value of a variable called MINIMUM, then the "analysis" routine will simply return immediately upon being called without having performed any tuning activity.

The next step in the "cold-sweep" routine is symbolized by block 950 on Figure 12B. This step sets the value of a variable called FAULT-CNTR equal to a constant called TRIES. This establishes the number of tuning attempts which will be made before a FAILURE flag is set indicating no successful tuning of the handpiece has been accomplished.

Next, the "cold-sweep" routine calls the "analysis" subroutine, as symbolized by block 952. The details of the "analysis" subroutine will now be described.

Referring to Figure 13, there is shown a flow chart of the "analysis" subroutine. The first step in the "analysis" subroutine is a test to determine the value of the RANGE variable as symbolized by block 956. If the RANGE variable is equal to a constant called MINIMUM, then processing flows immediately to step 958, which returns processing to step 960 in the "cold-sweep" routine shown in Figure 12B. Processing by steps 960 and following of the "cold-sweep" routine will be described in more detail below. If the value of the RANGE variable is found to be not equal to the constant MINIMUM, then a step 962 is performed wherein the LOOP flag is set to a false condition. This disables the operation of the phase "minimizer" routine previously described.

Next, a step 964 is performed to call a WINDOW subroutine. This routine calculates the minimum frequency and maximum frequency between which the voltage-controlled oscillator will be tuned during the tuning process. Basically the window subroutine calculates a variable called MINIMUM which sets the lower boundary of the tuning window. In the preferred embodiment, the variable MINIMUM is set at zero. The "window" subroutine"

also sets a variable called MAX-FREQ to a value of 4096. These two numbers establish a window for tuning of the voltage-controlled oscillator by variation of the fine tuning control signal HERTZ. The coarse tuning is controlled by the value of a variable COARSE which is set by a "chk-limit" subroutine to be described below to move the center frequency of the fine tuning window throughout the tuning band. Basically, the process is to set COARSE, sweep HERTZ and look for a resonance peak within the inner 50% of frequencies swept by HERTZ. If no resonance peak is found within this inner 50% of frequencies, hereafter called the ACCEPTABLE band, then COARSE is incremented to move the center frequency of the fine tuning window up 800 Hertz and the process is started again. The details of why only the inner 50% of frequencies of the fine tuning window are used will be given below.

The control signal HERTZ can vary between analog voltages which are proportional to digital values for the variable HERTZ. These values range between zero and 4096. When the value of the HERTZ variable is 2047, the voltage-controlled oscillator will operate at the center frequency established by the control signal COARSE. For each count of the variable HERTZ below the value 2047, the voltage-controlled oscillator will operate at a frequency of 1.6 hertz below the frequency established by the control signal COARSE. For every count of the variable HERTZ above a value of 2047, the frequency of the voltage-controlled oscillator will be 1.6 hertz above the frequency established by the control signal COARSE standing alone. The variable SWEEP-FREQ set by the subroutine "window" represented by block 964 in Figure 13 represents a pointer for the current operating frequency, i.e., the position within the fine-tuning window at which the voltage-controlled oscillator is currently operating. The variable MAX-FREQ establishes the upper limit for the window and an upper limit for the pointer variable SWEEP-FREQ.

It is now time to tune out the effect of the tuning inductor prior to a resonance tuning phase. To this end, the "analysis" subroutine calls the "precharge" subroutine, as symbolized by block 966 in Figure 13. The details of this subroutine are shown in the flow chart of Figure 14.

Referring to Figure 14, the first step in the "precharge" subroutine is to set the value of the variable HENRY to a constant to reduce the inductance of the tuning inductor to a minimum. This causes the microprocessor to set the value of the control signal HENRY to the driving circuitry for the tuning inductor such that the D.C. bias is increased to the point where flux saturation occurs and the inductance of the tuning inductor is thereby minimized. This process is symbolized by block 968.

Next, a delay of one second is implemented to allow the inductance of the tuning inductor to catch up with the changes in the value of the control signal HENRY. This step is symbolized by block 970. Thereafter, step 972 is performed wherein return to the next step in the "analysis" subroutine is performed.

Returning to consideration of the "analysis" subroutine, it is now necessary to set an appropriate power level to the probe. This process starts with the step symbolized by block 974 wherein the value of a variable BOUNDARY is saved. The BOUNDARY variable is an offset value controlling the power applied to the handpiece. Power applied to the handpiece is set at a level which is equal to the value of the variable BOUNDARY plus the value of a relative offset from the BOUNDARY value established by the position of the foot operated power control. The power control software, some embodiments, has numerous safety interlocks which will not allow power to be applied to the handpiece through use of the foot operated control unless certain conditions are satisfied. However, the value of the BOUNDARY variable is not protected and can be altered by the CPU without first satisfying the various conditions. Therefore, power can be applied by the software and the CPU to the handpiece simply by varying the value of the BOUNDARY variable. The step 974 saves the current BOUNDARY value for later restoration after the tuning process, since a nominal power level will be established by the software for the tuning process per se. This nominal power level is established in step 976 by setting the value of the BOUNDARY variable to the value of a constant called NOMINAL.

Steps 978 through 984 are preparation steps for setting the values of various variables prior to calling the subroutine "peak". This subroutine determines when a peak of load current has occurred and calculates the slope of the change in load current versus the change in operating frequency of the voltage-controlled oscillator. Steps 978 and 979 are optional and set flags labeled P-SLOPE and N-SLOPE. Step 980 sets the sweep frequency pointer variable SWEEP-FREQ to the value of the variable MINIMUM calculated by the window subroutine 964 to set the frequency pointer at the lower boundary of the tuning window. Step 981 sets the value of the HERTZ variable equal to the value of the variable MINIMUM to set the frequency of the voltage-controlled oscillator at the lowest frequency in the tuning window.

Step 982 sets the value of a variable I-PEAK equal to the value of the variable MINIMUM. The variable I-PEAK is used as a register to store the highest recorded value for the load current re-

corded to date.

Step 983 sets the value of a variable RESONANCE equal to the value of the variable MINIMUM. The RESONANCE variable is used to record the value of the variable SWEEP-FREQ at the point where the mechanical resonance frequency of the handpiece has been found.

The step 984 sets the value of a variable SLOPE equal to the value of the variable MINIMUM. The SLOPE variable is used to record the result of the slope calculation performed in the "peak" subroutine shown in Figure 17A. Thus, steps 978 through 984 simply initialize the value of the various variables such that they are in a known state prior to calling the subroutine "peak".

Step 986 represents the call to the subroutine "peak". The details of the "peak" subroutine and the subroutines called by this subroutine will be discussed below. Upon return from the "peak" subroutine, the step 994 is performed. This step decrements a variable FAULT-CNTR and is performed upon each return from the "peak" subroutine indicating that a another try to find the resonance frequency has been performed. Once the "peak" subroutine is called, the variable SWEEP-FREQ is continuously incremented and load current tests and slope calculations are performed at the various operating frequencies until the upper frequency in the tuning window has been reached. At that time, peak returns to step 994 of the "analysis" subroutine indicating that a complete sweep through the current tuning window has been performed.

Next, a step 997 is performed wherein the value of the variable FAULT-CNTR is compared to zero to determine is the allotted number of tries or sweeps has been performed. If the allotted number of tries has been performed and no resonance frequency has been found, step 997 will find FAULT-CNTR equal to zero, and will branch to step 999 where an error message will be sent to the console. Thereafter, in step 1001, a FAILURE flag will be set indicating that no resonance frequency has been found in the allotted number of tries. Then, return step 958 is performed to return to step 960 of the "cold-sweep" subroutine.

Returning to consideration of the "cold-sweep" subroutine, step 960 tests the condition of the FAILURE flag. If it is set, step 1003 is performed to disable a blink routine to stop blinking of the light-emitting diode (LED) on the front panel of the system. Next, a step 1005 is performed to disable to LED thereby keeping the LED dark and indicating to the user that the tuning has not been successful for some reason. The user can then investigate the problem.

If the test of step 960 determined that the FAILURE flag is not set, then a successful tuning phase has been performed and the VCO is now tuned to operate at the mechanical resonance frequency of the probe. In this event, a call to the "postcharge" subroutine is performed as symbolized by step 1009. The flow chart for this subroutine is given in 15.

Referring to 15, the first step in the "postcharge" subroutine is to set the TUNED flag to enable the power delivery routine in the main loop to deliver power on demand to the handpiece. Next, a step 1013 is performed to set a LOOP flag to enable operation by the "minimizer" routine to tune away any phase angle.

A step 1015 sets a flag FS-DOWN to artificially simulate a request for power. This is done because part of the function of the "postcharge" routine is to apply power for 3 seconds to allow the handpiece and tuning inductor to settle at an operating point which will be somewhat close to the actual operating point which be set following the "postcharge" routine. To apply power, the flag FS-DOWN must be set.

Next, a step 1017 is performed to set the variable HENRY and control signal HENRY to the value of a variable PREDICTED. This variable is a statistically empirically determined value which approximates the normal operating point for the tuning inductor when coupled to most probes.

Step 1019 raises the BOUNDARY variable to send full power to the handpiece. This is followed by a three second delay/settling time symbolized by step 1021.

Finally, in steps 1023 and 1025, respectively, the old boundary value is set to restore power to its original level and the old FS-DOWN flag status is restored. Processing then flows via step 1027 to step 1033 in the "cold-sweep" routine to enable the LED thereby indicating to the user that a successful tuning phase has been completed. Next, a step 1007 is performed to set a RELAPSE flag. This causes an elapsed timer to be reset to zero time. The elapsed timer is used to control a display on the front panel used by the user to keep track of how much energy has been dissipated inside the eye.

Returning to consideration of "cold-sweep", an optional step 1029 is performed to sound a tone or play a tune to indicate that the machine is done with the tuning phase and reminding the user to check the LED for status.

Step 1031 resets the bit of the MISTUNE variable that controls access to the ANALYSIS routine thereby disabling the analysis routine until the next call thereto.

Finally, a step 1033 is performed to turn off the VCO thereby preventing amplification of noise, and processing returns to step 938 of "sweeper" and thence to the calling process in the main loop.

Returning to the consideration of the "analysis" subroutine, if test 997 determines that the maximum number of tries to find the resonance frequency have not been expended, then a step 1035 to call the subroutine "ck-limit" is performed. This routine is detailed in Figure 16.

Referring to Figure 16, a flow chart of the "ck-limit" subroutine is shown. The purpose of this routine is to adjust the value of the variable COARSE to change the center frequency of the fine tuning window in an attempt to locate the window such that the resonance peak load current can be found within the center 50% of frequencies of the window. The first step in the "ck-limit" subroutine is to test the frequency represented by the variable RESONANCE against a variable HIGH RAIL. The variable RESONANCE has its value set by the "peak" routine to be described below at a peak load current frequency where the slope of the function of load current versus frequency is less than a predetermined amount. This test is symbolized by block 1037. The variable HIGH RAIL is set such that if the resonance frequency is found too far away from the center frequency of the tuning window, the variable COARSE will be adjusted to move the window to place the resonance frequency closer thereto. The variable HIGH RAIL is set at a frequency which is 75% up from the bottom of the tuning window. The value of this variable is calculated in the "window" subroutine of the "analysis" subroutine. The reason for the "ck-limit" subroutine is to alter the COARSE variable until the resonance peak occurs somewhere in the middle 50% of frequencies of the tuning window. This is desirable because certain voltage transients and other non-repeatable behaviors occur when operating in frequencies in the lower 25% and the upper 25% of the tuning window. Moving the tuning window in the aforedescribed manner tends to lead to finding the real resonance peak as opposed to a false peak caused by some non-repeatable phenomenon.

If the value of RESONANCE is found to be less than HIGH RAIL, step 1039 is performed to decrement the value of COARSE by the equivalent of 800 Hertz. If the value of RESONANCE is found to be greater than HIGH RAIL, step 1041 is performed to decrement the value of COARSE by the equivalent of 800 Hertz. Finally, in step 1043, the RAILED flag is set to indicate that the resonance peak was not found within the acceptable range of frequencies. Setting the RAILED flag vectors processing back to the "peak" routine to sweep the operating frequency through a new window. This is done via the return step 1045 which returns processing to step 1047 of the "analysis" routine.

Step 1047 on Figure 13 tests the RAILED flag and vectors processing back to step 978 if the flag is true.

If the RAILED flag is not set, step 1049 is performed to set the VCO at the resonance frequency. This is done by setting the value of the variable HERTZ equal to the value of the variable RESONANCE.

Next, conditions are set back to the way they were when "analysis" was called. First, FAULT-CNTR is set to zero in step 1051 and the second least significant bit of MISTUNE is set to 0 in step 1053. In step 1055 BOUNDARY is set back to its original value, and the LOOP flag is set to enable operations by the "minimizer" routine in step 1057. Finally, in steps 1059 and 1061, respectively, RANGE is set to MINIMUM and I-PEAK is set to MINIMUM. Thereafter, return to the calling process "cold-sweep" at step 960 is performed by step 958.

Referring to Figures 17A and 17B, the details of the "peak" subroutine are given in flow chart form. Block 1050 is the first step in the "peak" subroutine and implements a delay to allow the value of the tuning inductor to stabilized at the inductance established by the level of the control signal HERTZ set by step 981 in Figure 13.

Step 1052 is a test to determine whether the value of the variable HERTZ is less than the value of the variable MAX-FREQ calculated by the subroutine "window" in Figure 13 and establishing the upper frequency for the current tuning window. If the value of HERTZ is greater than the value of the maximum frequency, step 1054 is performed to return processing to step 994 of the "analysis" subroutine.

If HERTZ is less than the maximum frequency, step 1056 is performed to increment the value of the variable SWEEP-FREQ. Next, step 1058 is performed to set the value of the HERTZ variable equal to the value of the SWEEP-FREQ variable.

After the HERTZ variable has been established at its new level, the voltage-controlled oscillator changes frequency, and the amount of load current drawn at the new frequency will generally change from the amount of load current which was drawn at the previous operating frequency. It is necessary to know this new value for the load current. To that end, step 1060 is performed wherein the value of the present load current at the current operating frequency is read and stored as the variable CURRENT. This is accomplished by an input/output operation by the CPU 808 in Figure 1 reading the value of the signal CURRENT on line 820.

Step 1062 represents a test to compare the value of the CURRENT variable to the value of the previously highest recorded load current as represented by the variable I-PEAK. If CURRENT is less than I-PEAK, a jump symbolized by line 1064 to an again address is performed and a step 1066 is

performed to call the "recorder" subroutine. No new I-PEAK is recorded. If CURRENT is greater than I-PEAK, then a test 1068 is performed to determine if SWEEP-FREQ is within the lower reject range which is defined as the lower 25% of frequencies in the current tuning window. If this condition is true, a jump to again along line 1064 occurs and "recorder" is called and no new I-PEAK is recorded. If SWEEP-FREQ is not within the lower reject range, the test of step 1070 is performed to determine if SWEEP-FREQ is within an upper reject range. This range is defined as the upper 25% of frequencies in the current tuning window. If this condition is false, step 1072 is performed to record CURRENT as the new I-PEAK. If SWEEP-FREQ is within the upper reject range, a jump to again along line 1064 is performed.

After step 1072 is performed, a call to the "detector" subroutine is performed where the slope of the load current versus frequency function is compared to a constant. The slope is calculated by the "recorder" subroutine, so examination of that routine is now in order.

Referring to Figures 18A and 18B there is shown a flow chart of the "recorder" routine. The first step is to set a variable COUNTER to COUNTER + 2 as symbolized by step 1076. COUNTER is a pointer in a circular buffer used to store load current samples or points on the load current versus frequency curve. Each load current sample is two bytes in length, so incrementing the COUNTER is done by adding 2 to point to the next pair of addresses. This incrementation is symbolized by step 1076. Next, COUNTER is tested against zero in step 1078. If COUNTER has reached zero, the buffer has been filled (it is filled from the highest pair of addresses to the lowest pair of addresses), and COUNTER is reset to the top of the buffer by setting it equal to a constant BUFF-SIZE in step 1080. BUFF-SIZE is equal to the size of the buffer. If test 1078 determines that COUNTER is not zero, a step 1082 is performed to set an address pointer POINTER equal to BUFFER + COUNTER. BUFFER is the lowest address in the circular buffer, so step 1082 sets POINTER at an appropriate address in said buffer.

Next, a test 1084 is performed wherein POINTER is tested to see if it is still within the bounds of the buffer. Specifically, POINTER is compared to BUFFER and to BUFF-SIZE + BUFFER which mark the two ends of the buffer. If POINTER is within the buffer, the address pointed to by POINTER is loaded with the latest value of CURRENT in step 1086. If POINTER points to either end address of the buffer, a step 1088 is performed to set a variable TOP equal to the latest value of CURRENT as symbolized by line 1090.

Next, a step 1092 is performed to determine if POINTER is less than or equal to BUFFER, the lowest address in the buffer. If it is, POINTER is set equal to BUFFER + BUFF-SIZE in step 1094. This resets POINTER to the highest address in the buffer. If POINTER is greater than BUFFER, step 1096 is performed to set POINTER to POINTER - 2. Then a step 1098 is performed to set a variable BOTTOM equal to the contents of the buffer at the address pointed to by POINTER. Finally, in step 1100, a variable SLOPE is calculated as TOP - BOTTOM. SLOPE is thus equal to the latest value of CURRENT minus the value of CURRENT stored either at the highest pair of addresses in the buffer or the previous pair of addresses. SLOPE is proportional to the slope of the load current versus drive frequency function at the current drive frequency and load current coordinates. Then processing flows via step 1102 back to step 1104 of the "peak" subroutine which vectors processing back to step 1050 of "peak" along path 1106 to increment the drive frequency again.

Returning to step 1074 of "peak", the "detector" routine is called to evaluate SLOPE at the latest I-PEAK against a constant which will separate false peaks from the real resonant peak. Figure 19 is flow chart of the "detector" routine. The first step is a test to determine if SLOPE is less than a constant MIN-SLOPE. MIN-SLOPE is picked to separate the peak at 1110 in Figure 6 from the actual resonance peak at 876. The value of MIN-SLOPE is positive and greater than the slope of any spurious antiresonance peaks or other transients. Thus, unless SLOPE is greater than MIN-SLOPE, step 1112 is never reached. Step 1112 is the step where RESONANCE is set equal to SWEEP-FREQ thereby acknowledging that the frequency at which the latest value of I-PEAK was found is probably the actual mechanical resonance frequency of the probe under the current loading condition. Note that in the preferred embodiment, this tuning process is performed upon request by the user after the user attaches the probe, places it in water and presses a button (now shown) on the front panel requesting a tuning process.

After updating RESONANCE, the flag FAILURE is reset in step 1114 to indicate that tuning was successful.

If SLOPE was less than MIN-SLOPE, step 1116 is performed to start the process of rejecting the current peak as the legitimate resonance peak by setting I-PEAK to zero. Next, step 1118 sets RESONANCE to zero, and step 1120 sets the RAILED flag to zero. Finally, step 1122 returns processing to step 994 of "analysis" where processing proceeds as previously described.

Although the invention has been described in terms of the preferred and alternative embodiments disclosed herein, those skilled in the art will appre-

ciate many modifications which may be made without departing from the true spirit and scope of the invention. All such embodiments are intended to be included within the scope of the claims appended hereto.

Claims

1. A phacoemulsification apparatus for driving an ultrasonic handpiece including at least one crystal, comprising:
driver means for supplying a variable frequency, variable amplitude electrical driving signal to said handpiece;
an electrically tunable inductor means in said driver means for coupling to said crystal and altering the overall impedance of the combination of said handpiece and said tuning inductor; and
frequency tuning means coupled to said driver means and to said electrically tunable inductor means, for electrically tuning said tunable inductor to be at a minimum inductance during a resonance tuning phase and for tuning the frequency of said driving signal until a peak in the load current drawn by said handpiece is found where the slope of the function load current versus frequency of driving signal at said peak satisfies a predetermined criteria, and for causing said driver means to drive said handpiece at the frequency of said peak load current.

2. The apparatus of claim 1 further comprising phase tuning means coupled to said frequency tuning means and to said electrically tunable inductor and to said driver means, for, upon completion of said resonance tuning phase, determining the phase difference between the drive current of said driving signal and said load current and for electrically tuning said tunable inductor to reduce said phase difference to within a predetermined range of zero degrees.

3. The apparatus of claim 1 wherein said frequency tuning means includes means to reject spurious peaks in said load current by comparing the slope of the load current versus frequency of every peak in load current to a predetermined minimum positive slope.

4. The apparatus of claim 2 wherein said frequency tuning means includes means to reject spurious peaks in said load current by comparing the slope of the load current versus frequency of every peak in load current to a predetermined minimum positive slope.

5. The apparatus of claim 1 wherein said driving means includes a voltage controlled oscillator for creating said driving signal and having a coarse tuning input for receiving a coarse tuning signal that alters the frequency of said driving signal by a first factor per unit change in said coarse tuning signal and has a fine tuning input for receiving a fine tuning signal that alters the frequency of said driving signal by a second factor per unit change in said fine tuning signal.

6. The apparatus of claim 5 wherein said frequency tuning means includes a computer controlled by software means for causing said computer to generate said coarse and fine tuning signals such that said load current peak is located by setting said coarse tuning signal at a predetermined value and then sweeping said fine tuning signal through a predetermined range, and, if said peak is not found, for setting said coarse signal at a new value and then sweeping said fine tuning signal through a predetermined range and for repeating the above steps until said peak is located.

7. The apparatus of claim 2 wherein said driving means includes a voltage controlled oscillator for creating said driving signal and having a coarse tuning input for receiving a coarse tuning signal that alters the frequency of said driving signal by a first factor per unit change in said coarse tuning signal and has a fine tuning input for receiving a fine tuning signal that alters the frequency of said driving signal by a second factor per unit change in said fine tuning signal.

8. The apparatus of claim 7 wherein said frequency tuning means includes a computer controlled by software means for causing said computer to generate said coarse and fine tuning signals such that said load current peak is located by setting said coarse tuning signal at a predetermined value and then sweeping said fine tuning signal through a predetermined range, and, if said peak is not found, for setting said coarse signal at a new value and then sweeping said fine tuning signal through a predetermined range and for repeating the above steps until said peak is located.

9. The apparatus of claim 6 wherein said frequency tuning means rejects said peak if said peak is found at a frequency lying within the upper or lower 25% of the range of frequencies which said driving signal can assume for any level of said coarse tuning signal and full excursion of said fine tuning signal.

10. The apparatus of claim 8 wherein said frequency tuning means rejects said peak if said peak is found at a frequency lying within the upper or lower 25% of the range of frequencies which said driving signal can assume for any level of said coarse tuning signal and full excursion of said fine tuning signal.

11. An apparatus for driving an ultrasonically driven probe comprising:
first means for generating a driving signal for said probe and having an input for receiving a first control signal to determine the frequency of said

driving signal;
second means coupled to said first means to occasionally determine the mechanical resonant frequency of said probe under then existing conditions and to generate said first control signal to tune said first means for generating a driving signal at said mechanical resonant frequency of said probe;
a tuning inductor means for coupling said driving signal to said probe and having an input for receiving a second control signal which controls the amount of inductance of said tuning inductor and for changing inductance in accordance with said driving signal;
means coupled to said tuning inductor and to said first means and to said second means for determining the actual phase angle between the driving signal for said probe and the resulting driving signal current and for determining the difference between said actual phase angle and a desired range of phase angles and for generating said second control signal to tune said tuning inductor to minimize said phase angle after said second means has tuned said first means to generate said driving signal at said mechanical resonance frequency of said probe.

12. The apparatus of claim 11 wherein said second means includes means for determining said mechanical resonant frequency by sweeping the frequency of said driving signal through a predetermined range of frequencies and measuring the load current drawn by said probe and for selecting as said resonant frequency, that frequency where said load current is at a peak and the slope of a function relating load current versus frequency is greater than a predetermined value.

13. A method of driving an ultrasonically driven probe comprising the steps of:

(1) sending a driving signal having a frequency within a band of frequencies to be sent to said probe;

(2) sampling and storing the amount of drive current drawn by said probe;

(3) comparing said drive current sample to the highest drive current sample previously recorded for other drive signal frequencies in said band of frequencies;

(4) calculating the slope of a function relating each drive current sample to the corresponding drive signal frequency for substantially all said drive current samples;

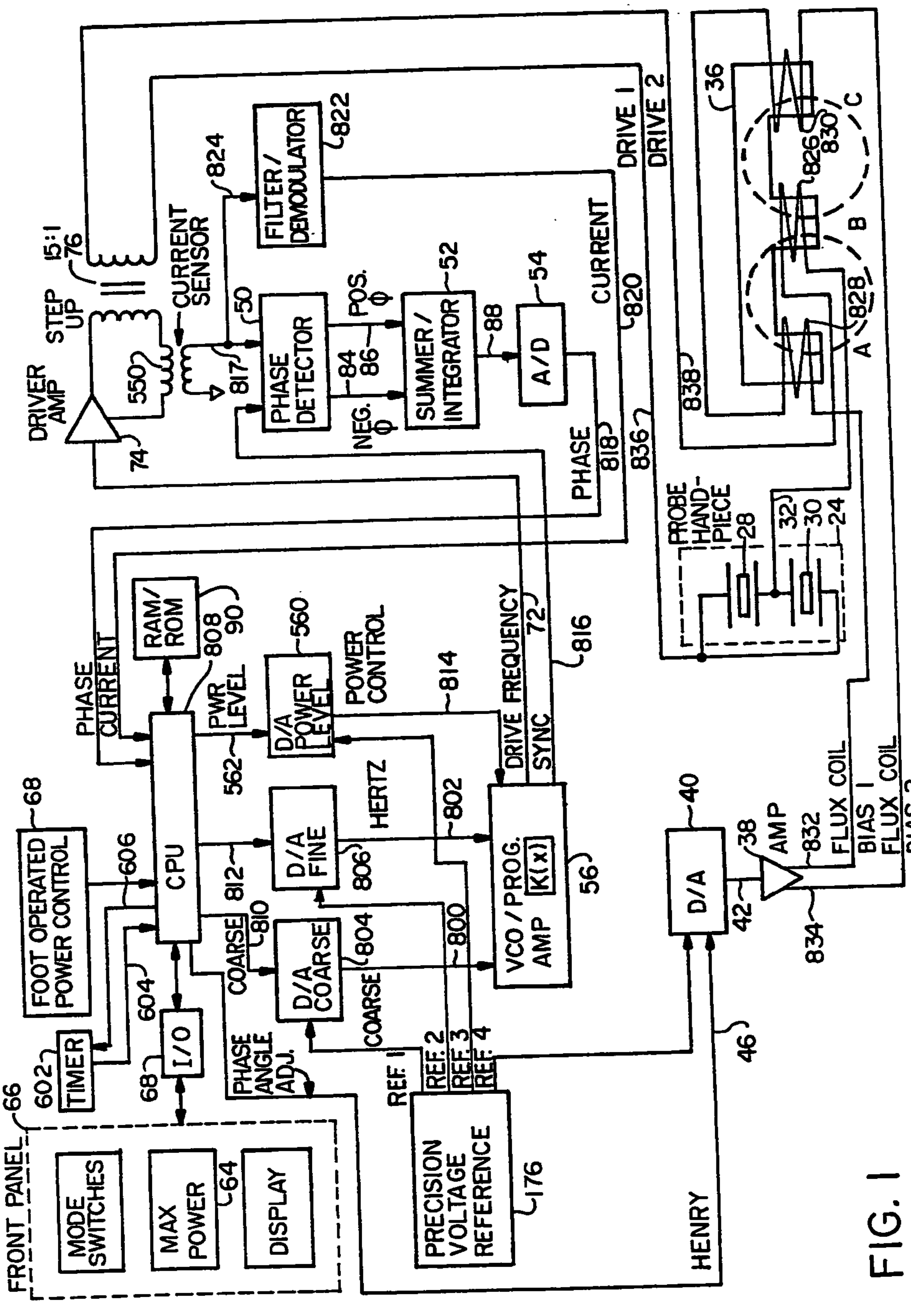
(5) incrementing the frequency of said driving signal;

(6) repeating steps 1 through 5 until a resonance frequency is found where the corresponding drive current sample is larger than all other drive current samples and wherein the slope of said function at said resonance frequency is greater than a predetermined constant selected to eliminate spurious current peaks caused by phenomena other than resonance from being mistaken as actual resonance peaks.

14. The method of claim 13 wherein said step of incrementing said frequency of said driving signal includes the steps of setting a coarse tuning signal at a predetermined value and incrementing a fine tuning signal to sweep through a range of frequencies defining a window, and if said resonance frequency is not found, for changing said coarse tuning signal to a new value and incrementing said fine tuning signal to sweep through a range of frequencies defining a new window, and repeating the above described steps until said resonance frequency is found, or a determination is made that said resonance frequency cannot be found.

15. The method of claim 14 wherein steps 5 and 6 include the steps of continuing to alter said coarse tuning and fine tuning signals until said resonance frequency is located within the center 50% of frequencies of any one of said windows or frequencies swept by the incrementation of said fine tuning signal.

16. the method of claim 15 wherein said step of altering said coarse tuning signal is carried out such that each said window of frequencies somewhat overlaps each other said window of frequencies.



FRONT PANEL
66
MODE SWITCHES
MAX POWER
64
DISPLAY
602
TIMER
68
I/O
604
606
FOOT OPERATED POWER CONTROL
68
CPU
RAM/ROM
808
90
PHASE
CURRENT
PWR LEVEL
562
D/A POWER LEVEL
560
POWER CONTROL
814
812
D/A FINE
806
HERTZ
802
810
COARSE
D/A COARSE
804
COARSE
800
VCO/PROG. AMP
K(x)
56
DRIVE FREQUENCY
SYNC
72
816
PHASE ANGLE ADJ.
REF. 1
REF. 2
REF. 3
REF. 4
PRECISION VOLTAGE REFERENCE
176
HENRY
46
D/A
40
42
38
AMP
832
834
FLUX COIL BIAS 1
FLUX COIL BIAS 2
DRIVER AMP
74
550
STEP UP
15:1
76
CURRENT SENSOR
817
50
824
FILTER/DEMODULATOR
822
PHASE DETECTOR
84
86
NEG. Φ
POS. Φ
SUMMER/INTEGRATOR
52
88
A/D
54
CURRENT
820
PHASE
818
836
DRIVE 1
DRIVE 2
838
PROBE HAND-PIECE
28
32
30
24
36
826
830
828
A
B
C

FIG. 1

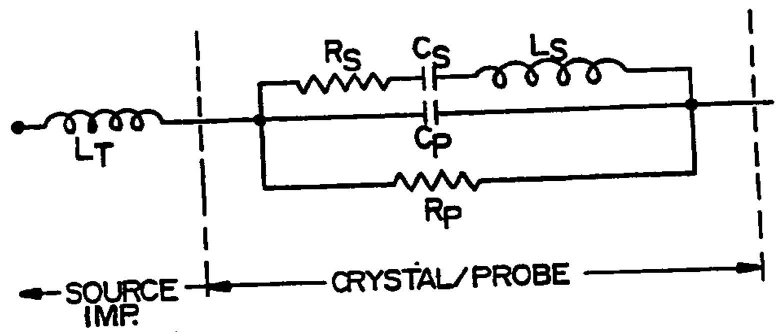


FIG. 2

$$(A)\ \omega_S = \frac{1}{\sqrt{L_S C_S}} \qquad (B)\ L_T = \frac{(R_S \parallel R_P)^2 C_P}{1 + \omega_S^2 C_P^2 (R_S \parallel R_P)^2} \quad \text{AT } \omega_S$$

FIG. 3

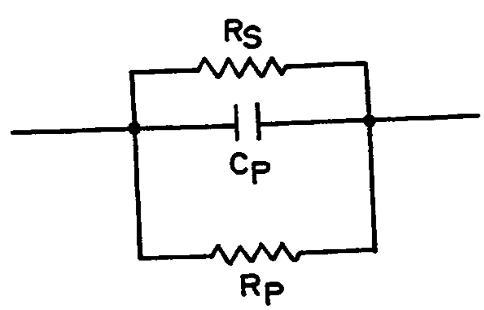
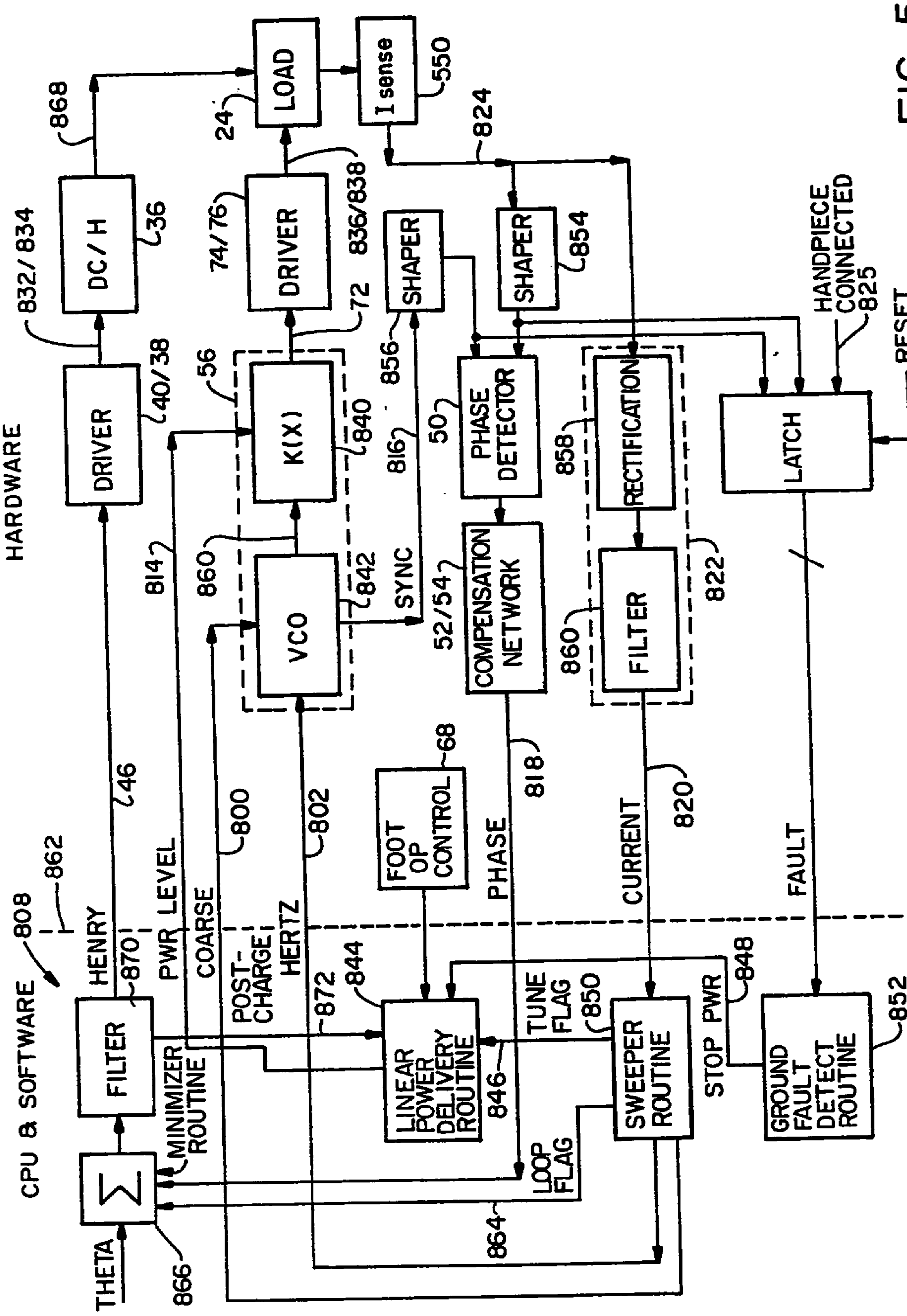


FIG. 4



HARDWARE
CPU & SOFTWARE
808
862
DRIVER
40/38
832/834
DC / H
36
868
LOAD
24
I sense
550
824
DRIVER
74/76
836/838
72
K(X)
56
840
816
VCO
860
842
SYNC
814
SHAPER
856
SHAPER
854
PHASE DETECTOR
50
COMPENSATION NETWORK
52/54
RECTIFICATION
858
FILTER
860
822
LATCH
HANDPIECE CONNECTED
825
RESET
46
800
802
FOOT OP CONTROL
68
PHASE
818
CURRENT
820
FAULT
HENRY
870
PWR LEVEL
COARSE
POST-CHARGE
HERTZ
872
844
FILTER
MINIMIZER ROUTINE
LINEAR POWER DELIVERY ROUTINE
846
TUNE FLAG
850
SWEEPER ROUTINE
STOP PWR
848
GROUND FAULT DETECT ROUTINE
852
LOOP FLAG
864
THETA
866

FIG. 5

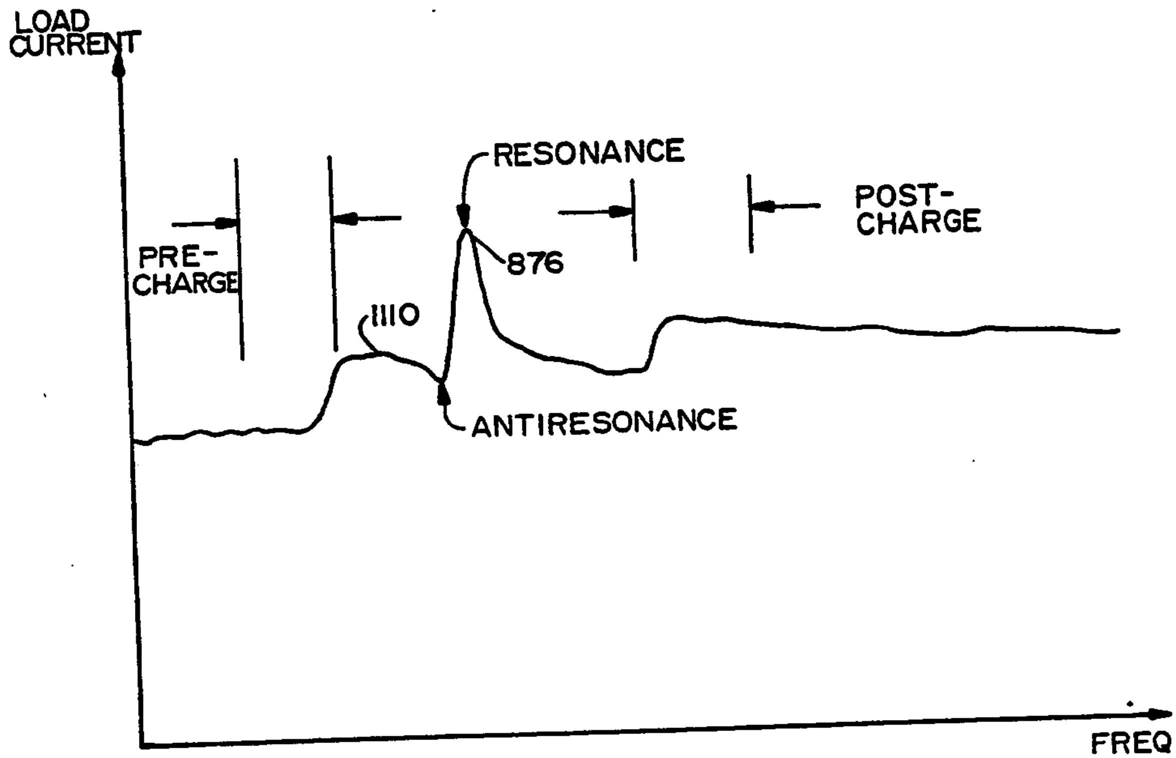

LOAD CURRENT
RESONANCE
PRE-CHARGE
POST-CHARGE
876
1110
ANTIRESONANCE
FREQ.

FIG. 6

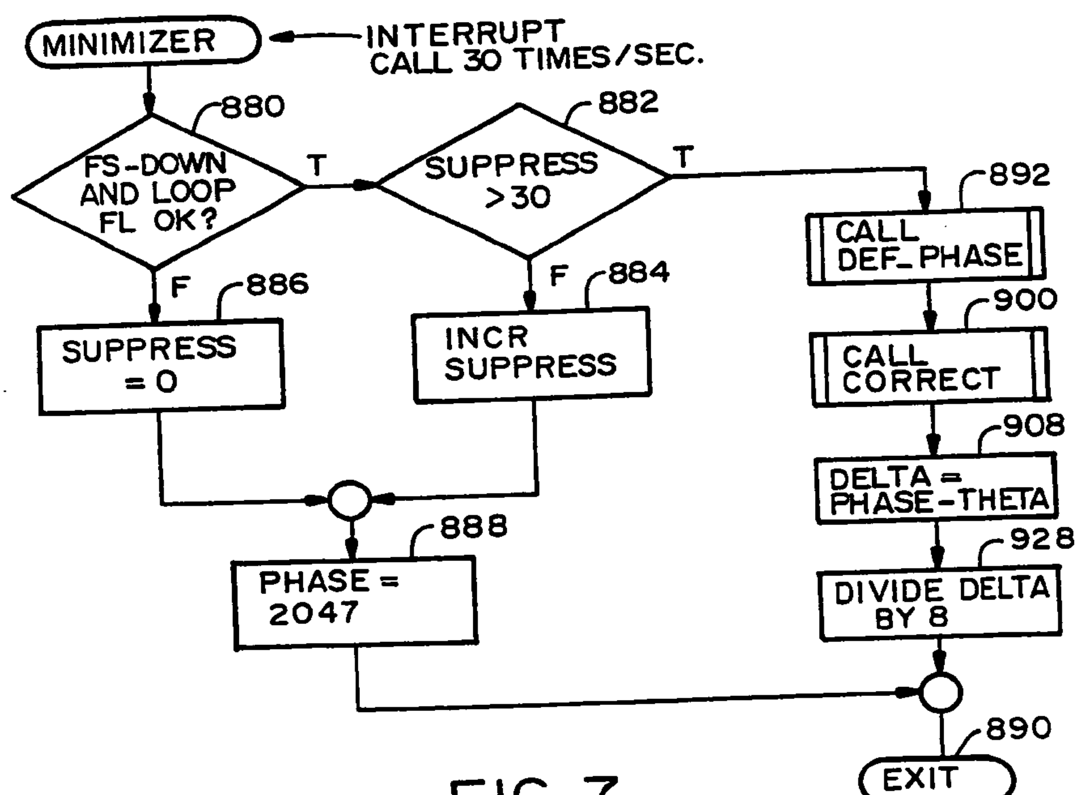

MINIMIZER
INTERRUPT CALL 30 TIMES/SEC.
880
FS-DOWN AND LOOP FL OK?
T
882
SUPPRESS >30
T
892
CALL DEF_PHASE
F
886
SUPPRESS = 0
F
884
INCR SUPPRESS
900
CALL CORRECT
908
DELTA = PHASE-THETA
888
PHASE = 2047
928
DIVIDE DELTA BY 8
890
EXIT

FIG. 7

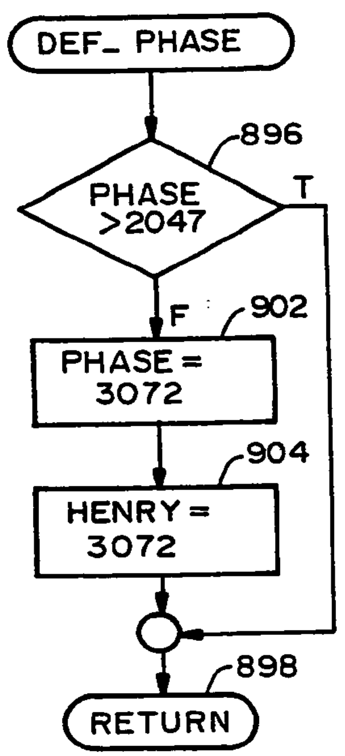


FIG. 8

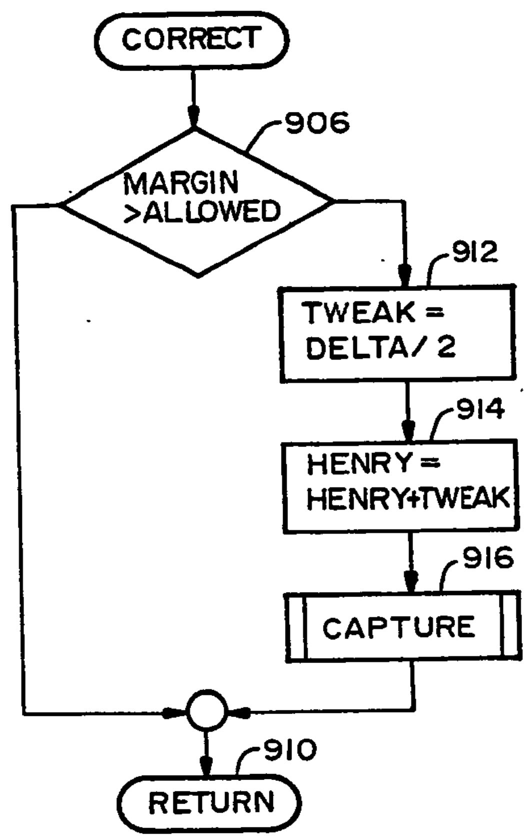


FIG. 9

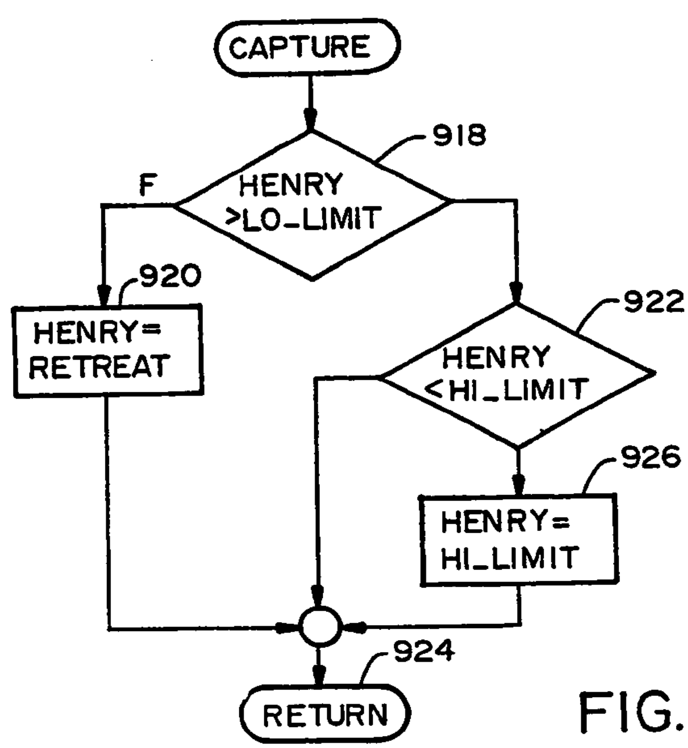


FIG. 10

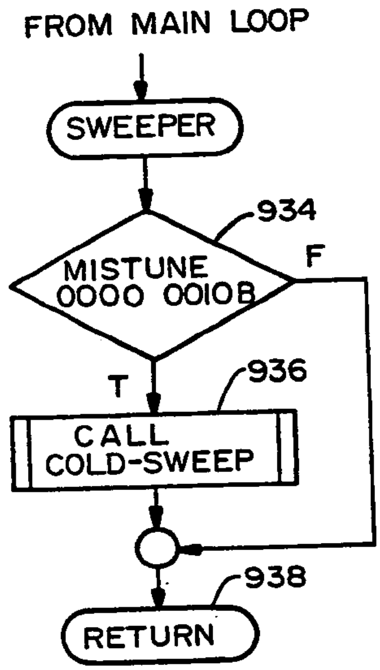


FIG. 11

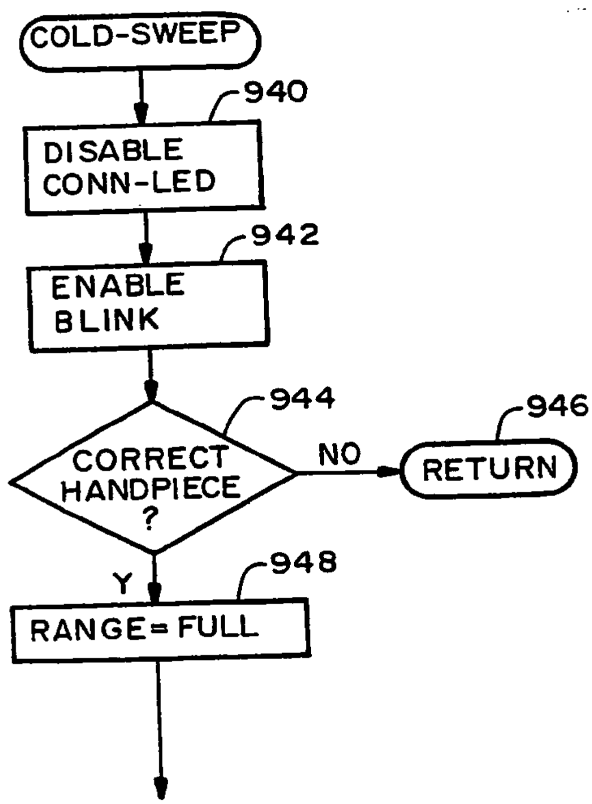


FIG. 12A

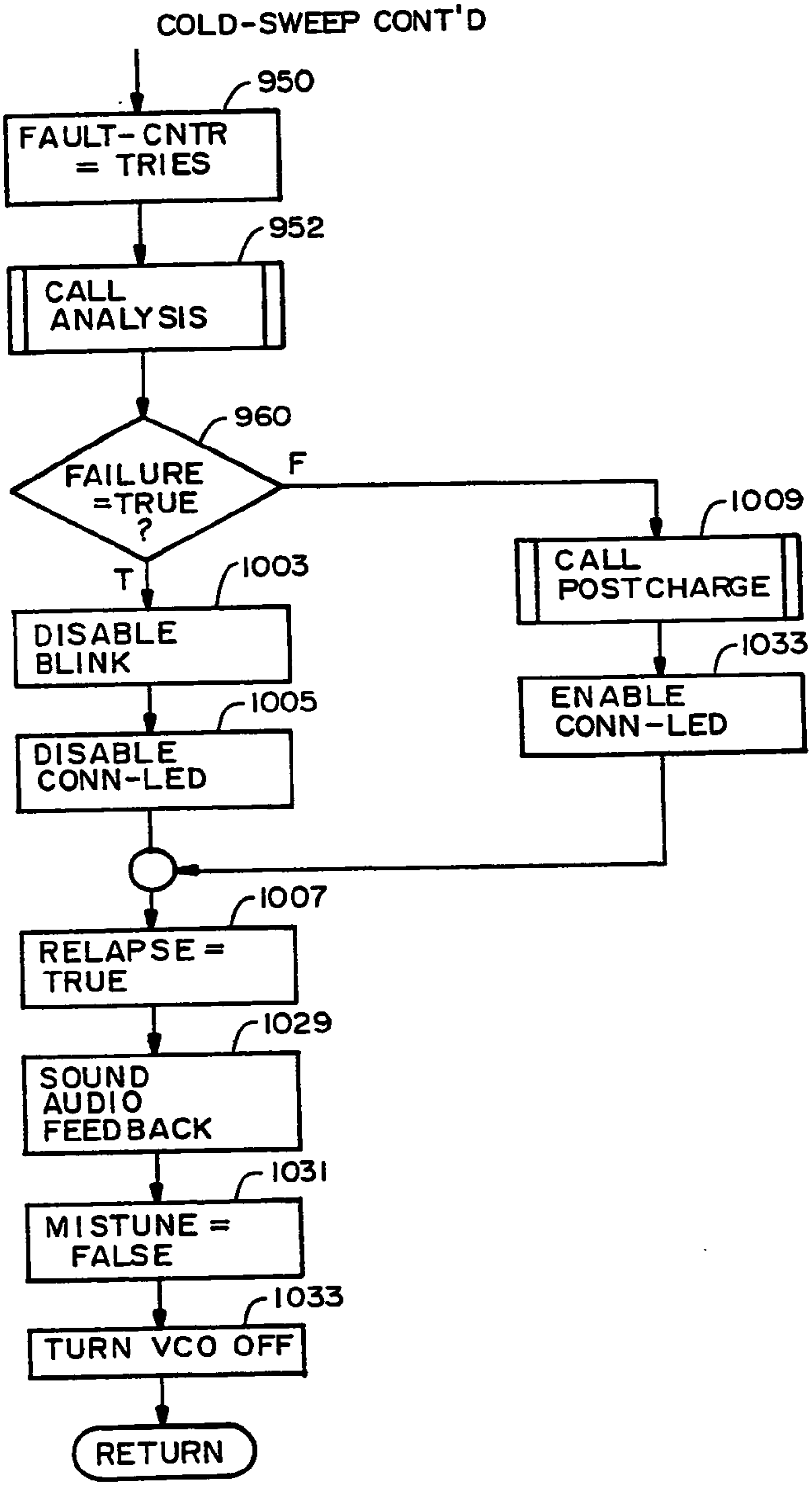

COLD-SWEEP CONT'D
950
FAULT-CNTR = TRIES
952
CALL ANALYSIS
960
FAILURE =TRUE ?
F
T
1009
CALL POSTCHARGE
1003
DISABLE BLINK
1033
ENABLE CONN-LED
1005
DISABLE CONN-LED
1007
RELAPSE = TRUE
1029
SOUND AUDIO FEEDBACK
1031
MISTUNE = FALSE
1033
TURN VCO OFF
RETURN

FIG. 12B

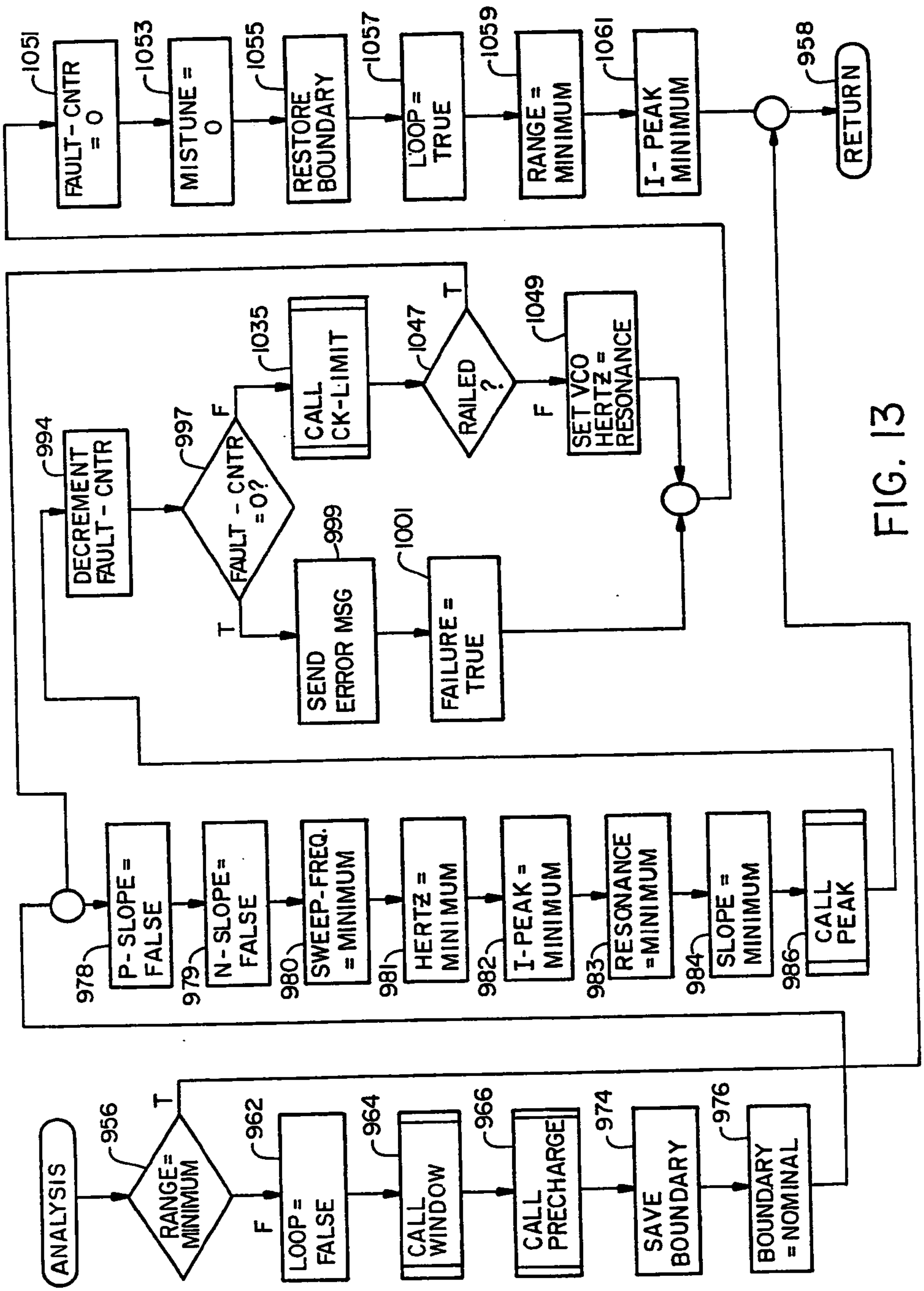

ANALYSIS
956
RANGE= MINIMUM
T
F
962
LOOP = FALSE
964
CALL WINDOW
966
CALL PRECHARGE
974
SAVE BOUNDARY
976
BOUNDARY = NOMINAL
978
P-SLOPE = FALSE
979
N-SLOPE = FALSE
980
SWEEP-FREQ. = MINIMUM
981
HERTZ = MINIMUM
982
I-PEAK = MINIMUM
983
RESONANCE = MINIMUM
984
SLOPE = MINIMUM
986
CALL PEAK
994
DECREMENT FAULT-CNTR
997
FAULT-CNTR = 0?
999
SEND ERROR MSG
1001
FAILURE = TRUE
1035
CALL CK-LIMIT
1047
RAILED ?
1049
SET VCO HERTZ = RESONANCE
1051
FAULT-CNTR = 0
1053
MISTUNE = 0
1055
RESTORE BOUNDARY
1057
LOOP = TRUE
1059
RANGE = MINIMUM
1061
I-PEAK MINIMUM
958
RETURN

FIG. 13

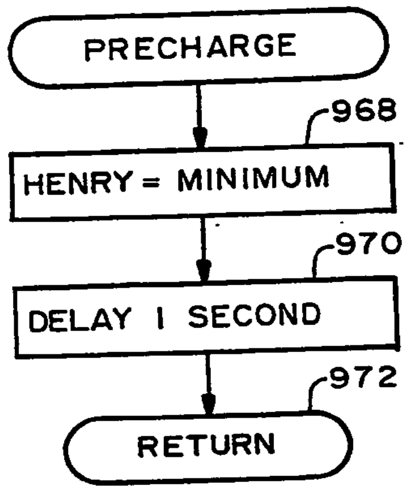


FIG. 14

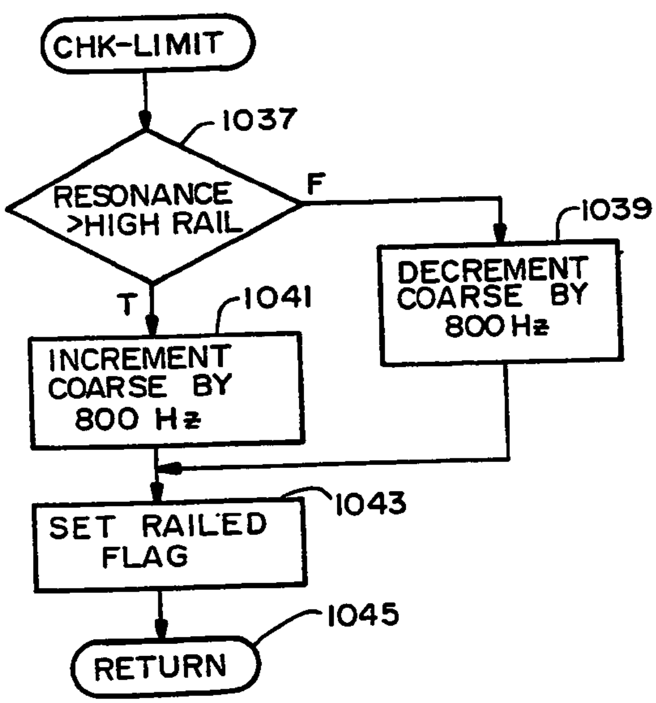


FIG. 16

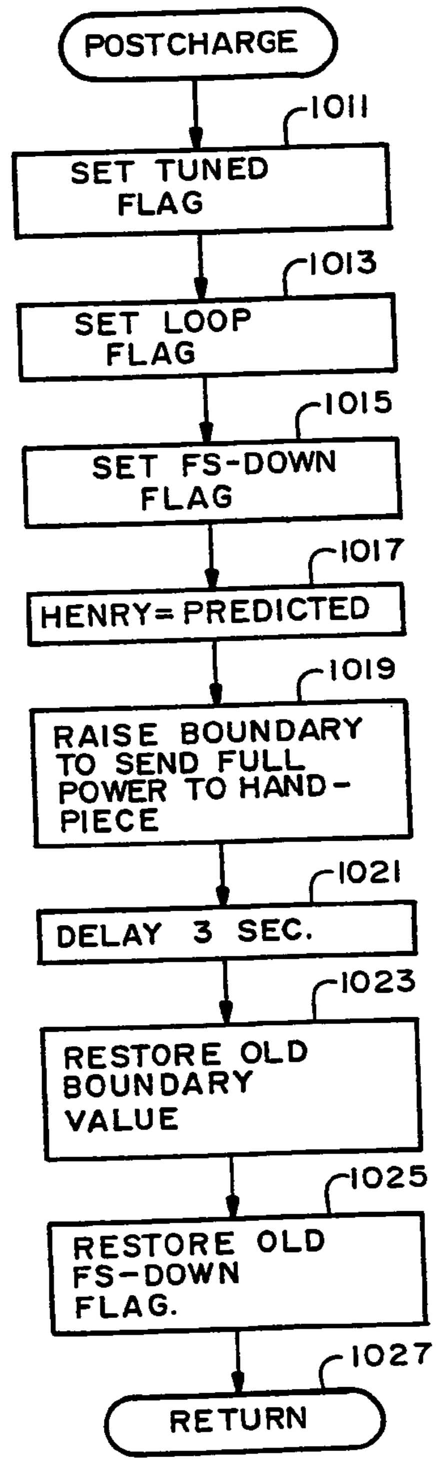


FIG. 15

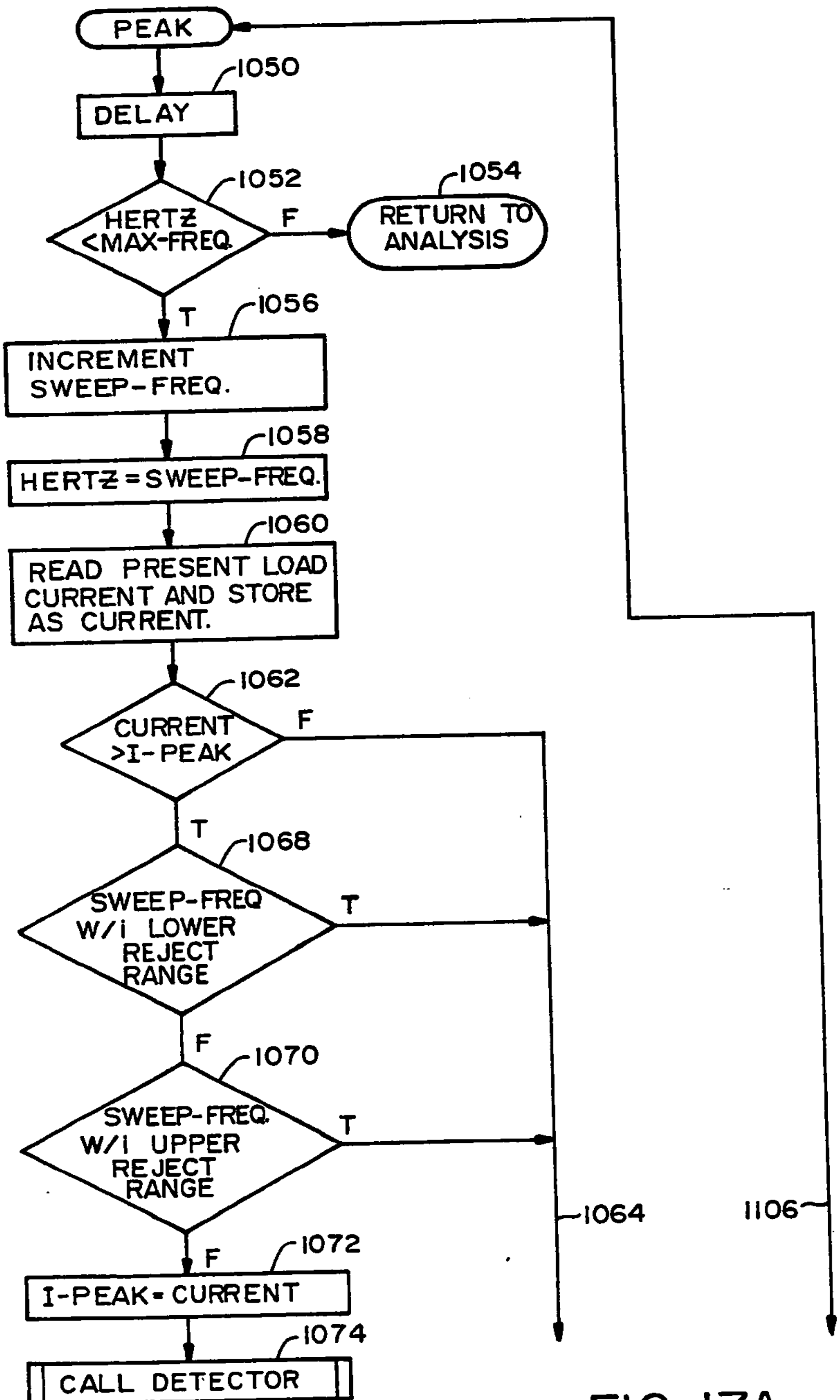

PEAK
1050
DELAY
1052
HERTZ
<MAX-FREQ
F
1054
RETURN TO
ANALYSIS
T
1056
INCREMENT
SWEEP-FREQ.
1058
HERTZ = SWEEP-FREQ.
1060
READ PRESENT LOAD
CURRENT AND STORE
AS CURRENT.
1062
CURRENT
>I-PEAK
F
T
1068
SWEEP-FREQ
W/I LOWER
REJECT
RANGE
T
F
1070
SWEEP-FREQ.
W/I UPPER
REJECT
RANGE
T
F
1072
I-PEAK = CURRENT
1074
CALL DETECTOR
1064
1106

FIG. 17A

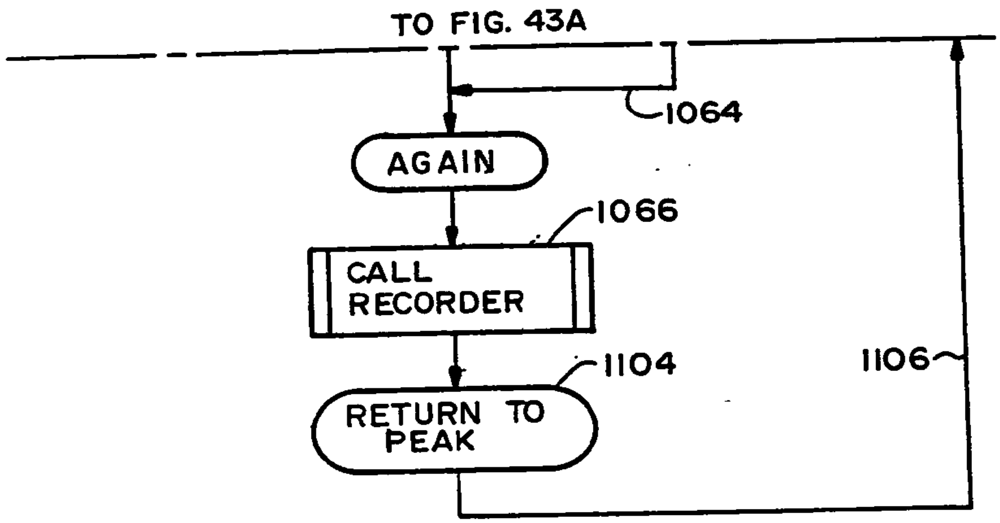


FIG. 17B

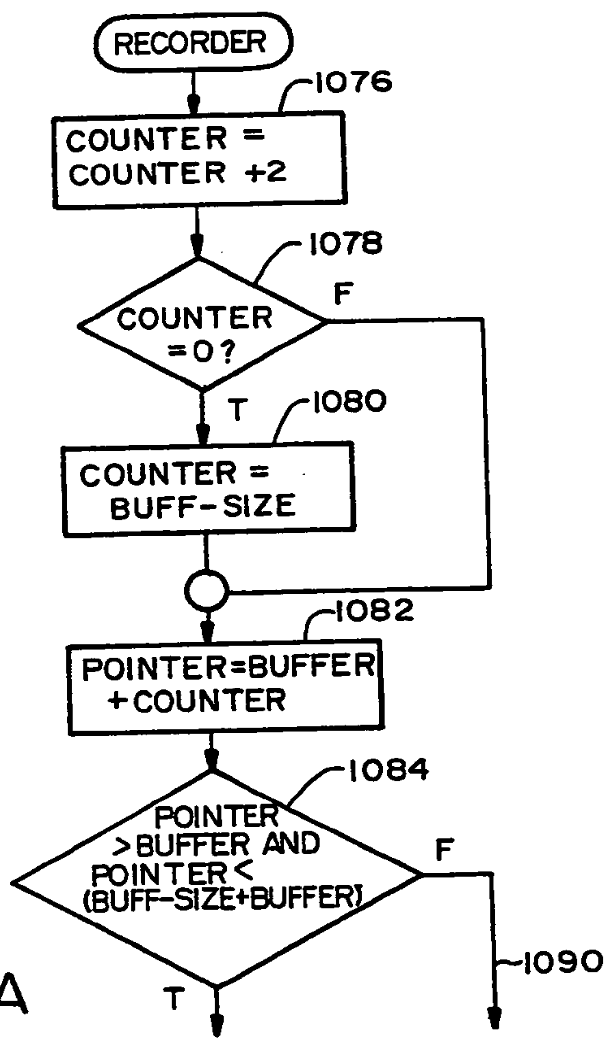


FIG. 18A

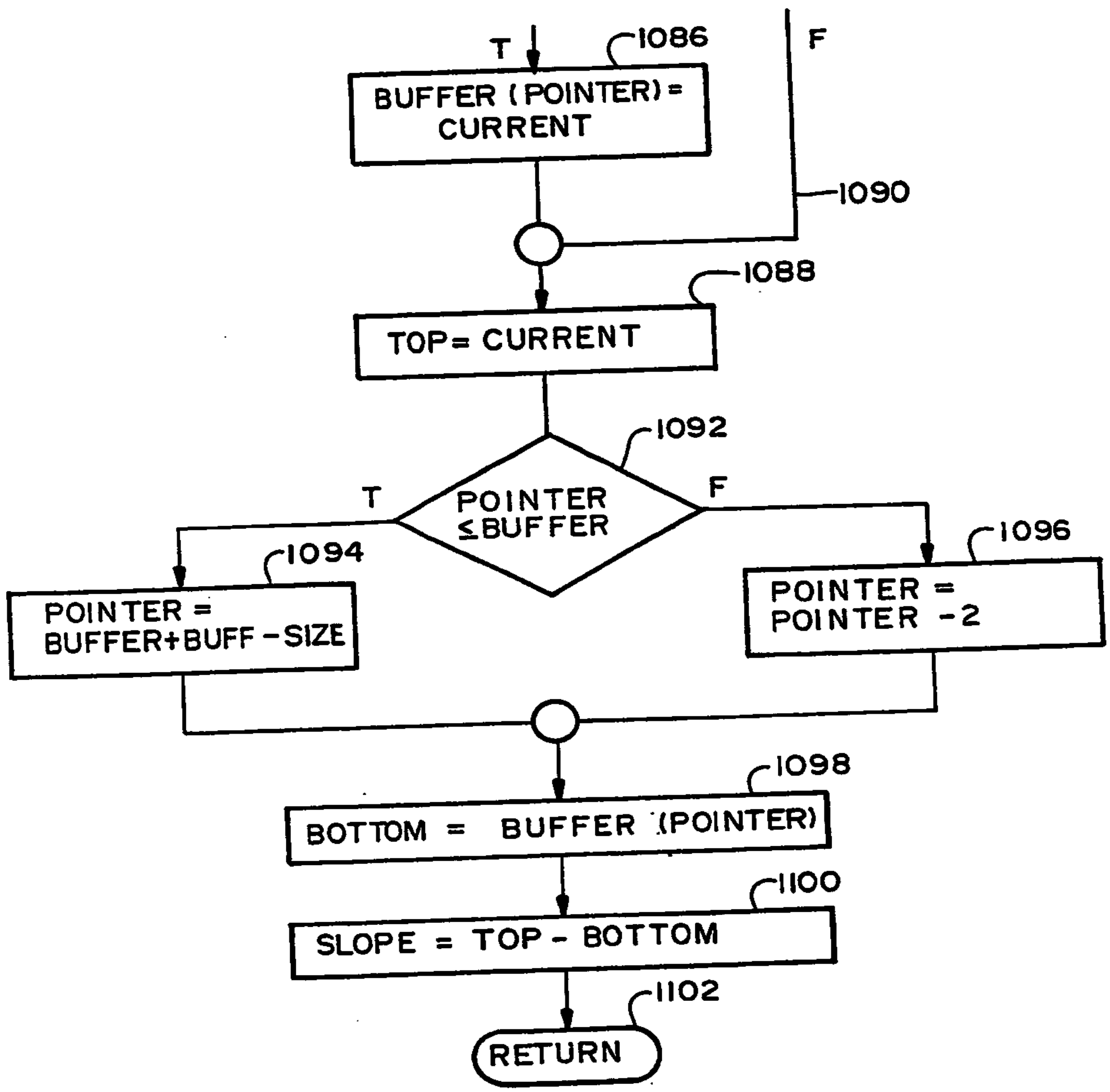

T
1086
F
BUFFER (POINTER) = CURRENT
1090
1088
TOP= CURRENT
1092
T
POINTER ≤BUFFER
F
1094
1096
POINTER = BUFFER+BUFF-SIZE
POINTER = POINTER -2
1098
BOTTOM = BUFFER (POINTER)
1100
SLOPE = TOP - BOTTOM
1102
RETURN

FIG. 18B

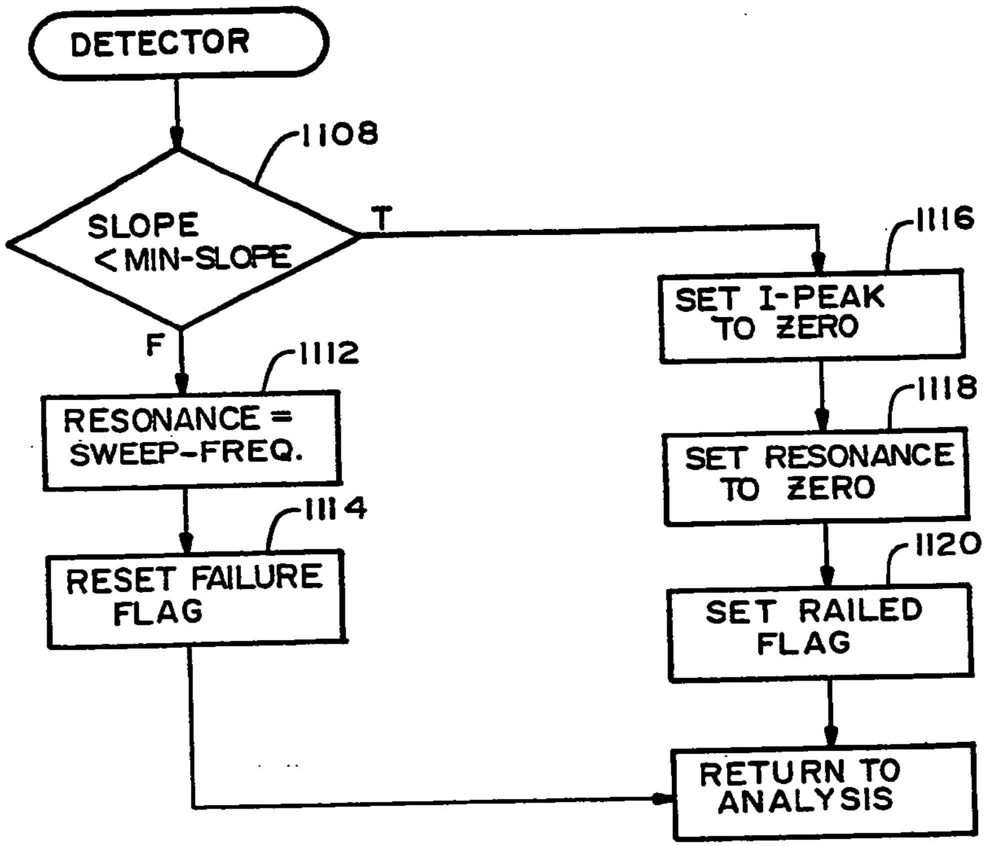

DETECTOR
1108
SLOPE
< MIN-SLOPE
T
F
1112
RESONANCE =
SWEEP-FREQ.
1114
RESET FAILURE
FLAG
1116
SET I-PEAK
TO ZERO
1118
SET RESONANCE
TO ZERO
1120
SET RAILED
FLAG
RETURN TO
ANALYSIS

FIG. 19

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Office européen des brevets

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(54) **Linear power control for ultrasonic probe with tuned reactance.**

(57) There is disclosed herein a driver system for an ultrasonic probe for allowing a user to have proportional control of the power dissipated in the probe in accordance with the position of power dissipation controls operable by the user and for automatically tuning upon user request such that the driving frequency is equal to the mechanical resonant frequency of said probe and such that the reactive component of the load impedance represented by said probe is tuned out. The system uses a tunable inductor in series with the piezoelectric crystal excitation transducer in the probe which has a flux modulation coil. The bias current through this flux modulation coil is controlled by the system. It is controlled such that the inductance of the tunable inductor cancels out the capacitive reactance of the load impedance presented by the probe when the probe is being driven by a driving signal which matches the mechanical resonance frequency of the probe. The resulting overall load impedance is substantially purely resistive. The system measures the phase angle and monitors the load current. This information is used to determine the mechanical resonance frequency by sweeping through a band of driving frequencies and finding the peak load current where the slope of the load current versus frequency function is greater than a predetermined constant. After the automatic tuning to the resonant frequency, the system automatically adjusts the bias current flowing through the flux modulation coil to maintain the substantially purely resistive load impedance for changing power levels. There is also disclosed herein an analog circuit to measure the Phase angle for the load driving signal and to adjust the frequency of the driving signal for best performance. This system includes an integrator to eliminate the effect of offset errors caused by operational amplifiers.

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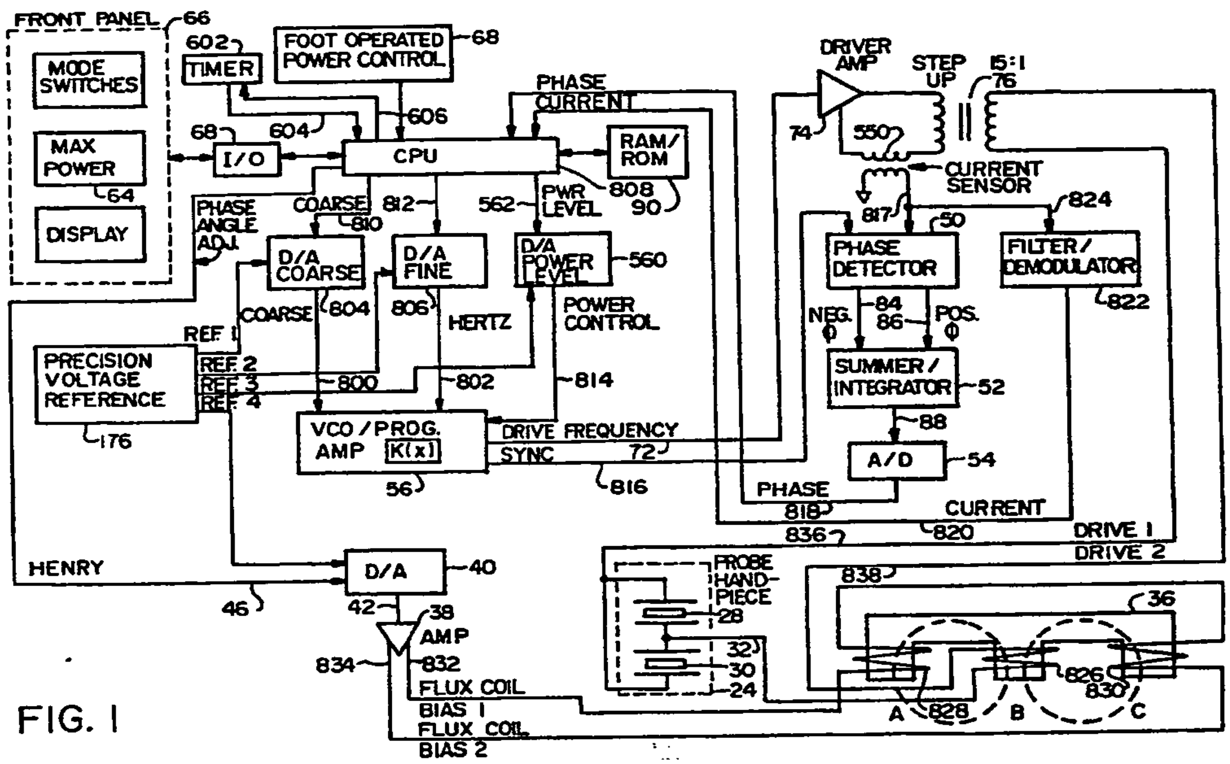
FRONT PANEL
66
MODE SWITCHES
MAX POWER
64
DISPLAY
602
TIMER
FOOT OPERATED POWER CONTROL
68
I/O
604
606
CPU
RAM/ROM
808
90
PHASE CURRENT
PHASE ANGLE ADJ.
COARSE
810
812
562
PWR LEVEL
D/A COARSE
D/A FINE
D/A POWER LEVEL
560
COARSE
804
806
HERTZ
POWER CONTROL
REF 1
PRECISION VOLTAGE REFERENCE
REF 2
REF 3
REF 4
800
802
814
176
VCO / PROG. AMP
K(x)
DRIVE FREQUENCY
SYNC
72
56
816
DRIVER AMP
74
550
STEP UP
15:1
76
CURRENT SENSOR
817
824
50
PHASE DETECTOR
FILTER/ DEMODULATOR
822
NEG. Φ
84
86
POS. Φ
SUMMER/ INTEGRATOR
52
88
A/D
54
PHASE
818
CURRENT
820
836
DRIVE 1
DRIVE 2
HENRY
D/A
40
46
42
38
AMP
834
832
FLUX COIL BIAS 1
FLUX COIL BIAS 2
PROBE HAND-PIECE
28
32
30
24
838
36
826
830
A
828
B
C

FIG. 1

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 89 11 6919

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
X	EP-A-0 270 819 (ALCON LABORATORIES INC.) * Abstract; figure 1; claims 1,4 *	1,2,11	A 61 F 9/00
Y		5-8	
Y	US-A-4 736 130 (W.L. PUSKAS) * Abstract; figure 1 *	5-8	
A	EP-A-0 247 752 (F.F.H. RAWSON)		
A	FR-A-2 607 651 (KALTENBACH & VOIGT GmbH & CO.)		

TECHNICAL FIELDS SEARCHED (Int. Cl.5)

B 06 B 1

The present search report has been drawn up for all claims

Place of search	Date of completion of search	Examiner
The Hague	16 August 91	DE HEERING P.

CATEGORY OF CITED DOCUMENTS

X: particularly relevant if taken alone
Y: particularly relevant if combined with another document of the same category
A: technological background
O: non-written disclosure
P: intermediate document
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